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DEVELOPMENT OF A SUITABLE ANECHOIC TREATMENT FOR THE ASD SONIC FATIGUE FACILITY

TECHNICAL DOCUMENTARY REPORT ASD-TDR-62-985

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FOREWORD

This report was prepared by Armour Research Foundation of Illinois Institute of Technology, Chicago, Illinois on Air Force Contract AF 33(657)-7434, Project No. 4437, "Development of a Suitable Anechoic Treatment for the ASD Sonic Fatigue Facility". The work was administered under the direction of the Sonic Branch. Mr. W. K. Shilling was task engineer.

The main part of the work was done between November 1961 and April 1962 and the program was extended under a supplemental agreement from July to October 1962. The project leader was F. G. Tyzzer and other contributors are L. D. Williams, H. H. Hall, W. E. Lawrie, C. S. Caccavari, and W. C. Sperry.

ABSTRACT

Results are given for a research program leading to the design of an anechoic treatment for the test chamber of the ASD high intensity sound facility. The acoustical requirements for 96 percent absorption coefficient at normal incidence for a frequency range of 50 - 7000 cps and for sound pressure levels up to 160 db and the mechanical requirements for a collapsible treatment presented novel problems in design. The requirements were met by a treatment, six feet thick, composed of six layers of absorbing material irregularly spaced with the acoustical resistances per layer increasing from values for layers at the incidence sound side to higher values for layers near the room surfaces. Tests in the high intensity impedance tube facility designed for the program showed that the normal incidence absorption coefficient of the treatment was 96 percent or higher over most of the frequency range from 50 - 7000 cps at sound pressure levels from 130 to 160 db. Fairly satisfactory results were also obtained for a five layer treatment subsequently designed. Etched polyurethane foam supported by wire screens was initially chosen as the layer material because of its resistance to damage in small scale life tests at particle velocities corresponding to a sound pressure level of 160 db. In subsequent accelerated life tests in the siren facility at North American Aviation, Columbus, Ohio, there was no significant damage to a four by four foot specimen of material after 105 hours at sound pressure levels between 165 and 170 db except for failure of the supporting wire screens at about 78 hours.

This technical documentary report has been reviewed and is approved for publication.

Webster W. Plourd

WEBSTER W. PLOURD
Colonel, USAF
Asst Deputy for Test and Support

REVIEW AND COORDINATION OF ASD TECHNICAL DOCUMENTARY

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Project Engineer:

William K. Shilling III

WILLIAM K. SHILLING III
Sonic Branch, Environmental Division
Directorate of Engineering Test
Deputy for Test and Support

Concurred In:

for Carl E Reichert

WILLIAM J. DuBOIS, Lt. Col. USAF
Acting Director of Engineering Test
Deputy for Test and Support

Concurred In:

Hugh S. Lippman

HUGH S. LIPPMAN
Technical Director
Deputy for Test and Support

Approved by:

Webster W. Plourd

WEBSTER W. PLOURD
Colonel, USAF
Asst Deputy for Test and Support

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SYMBOLS

The units assigned to the symbols are used throughout the report except when other units are used specifically mentioned. However, when symbols are used in ratios such as d/λ it is to be understood that the symbols have the same units.

Symbol	Units	Definition
a	cm	Radius of impedance tube
A	sabins	Equivalent area in ft^2 of a perfectly absorptive surface
B	ft^2	Room coefficient equal to the total number of sabins divided by one minus the average absorption coefficient of the room surfaces
c	cm/sec	Velocity of sound
d	inches	Length of air space between layers, also length of horn
E	$watts/cm^2$	Sound intensity, energy loss per unit area
f	cps	Frequency
j		Symbol for imaginary part of impedance $(-1)^{1/2}$
K	$dynes/cm^2$	Volume coefficient of elasticity of air
ℓ	inches	Thickness of absorbing material
m	$grams/cm^2$	Surface density
M	sec	Surface density dividing by the characteristic impedance of air, $m/\rho c$
p	$dynes/cm^2$	RMS value of instantaneous sound pressure
q		Horn flare constant
r	$dyne\ sec/cm^3$	Specific acoustic resistance, acoustic resistance per unit area, real part of z

SYMBOLS (Continued)

Symbol	Units	Definition
R		Normalized specific acoustic resistance, $r/\rho c$
S	cm^2	Area
T	sec	Reverberation time, for a 60 db sound decay
u	cm/sec	RMS particle velocity in a sound wave, also linear DC velocity of air
U	cm^3/sec	RMS volume velocity in a sound wave, also DC flow velocity of air
v	cm/sec	RMS value of velocity of vibration
V	ft^3	Volume of room
w	dynes sec/cm^3	Characteristic impedance for sound in a medium or material
W		Characteristic impedance w normalized by dividing by ρc for air
X		Imaginary part of specific impedance z normalized by dividing by ρc for air
Y		Porosity of a material, ratio of volume of voids to total volume
z	dyne sec/cm^3	Specific impedance, acoustical impedance per unit area, p/u
z'	dyne sec/cm^5	Acoustical impedance
Z		Normalized specific impedance, $z/\rho c$
α	per cent	Absorption coefficient at a surface, ratio of energy absorbed to incident energy
α_N	percent	Absorption coefficient for sound at normal incidence at a surface
β	1/cm	Phase shift in radians per unit length for sound in a medium or material, imaginary part of propagation constant

SYMBOLS (Continued)

Symbol	Units	Definition
Γ	1/cm	Propagation constant for sound in a material or medium $\Gamma = \alpha + j\beta$
α	1/cm	Attenuation constant in nepers per unit length for sound in a medium or material, real part of propagation constant
λ	cm	Wavelength of sound, c/f
π		3.1416
ρ	gram/cm^3	Density
ρc	dyne sec/cm^3	Characteristic impedance of air
μ	1/sec	Angular frequency $2\pi f$

SECTION I

INTRODUCTION AND SUMMARY

The design of a wall and ceiling treatment for the ASD sonic fatigue facility (Ref. 1) involved not only rather severe acoustical requirements but also the choice of material and supporting structures to satisfy non-acoustical requirements such as low cost, collapsibility, and durability under extreme of temperature, humidity and sound pressure level. The desired acoustical characteristic was a normal incidence absorption greater than 96 percent for a frequency range between 20 and 10,000 cps at sound pressure levels as high as 160 db. The maximum thickness of the treatment was six feet, which actually limited the lower frequency to about 50 cps. The choice of materials and supporting structures involved ambient conditions with relative humidity close to 100 percent and temperature up to 250°F (normal running conditions were estimated as 80 percent relative humidity and air temperature of 180°F), a total surface density less than 10 lb/ft^2, the ability to collapse and store the treatment when the facility is used as a reverberant space, and durability of the treatment with respect to damage by normal handling and by the effects of the intense sound. The cost of the treatment was also an important factor and required the use of commercially available materials of fairly low cost.

Layer type absorbing treatments were selected for measurement and study because preliminary calculations showed that such systems would meet the acoustic and mechanical requirements and because, measurements of normal absorption over a wide frequency range are possible for such systems. Testing at high sound levels was also desirable because it was believed that many of the acoustical properties of absorbing materials would vary with sound level in the range above 130 to 140 db.

A high intensity test facility was developed which consisted of three impedance tubes with power sources capable of producing a 160 db sound pressure level in a progressive plane wave in two 3-inch diameter tubes between 50 and 2000 cps and in a 0.75-inch diameter tube from 1500 to 7000 cps.

Measurements of DC flow resistance for large flow velocities were made on a large number of absorbing materials and the AC resistance was measured for materials suitable for layer systems. The resistances of all materials increased with increasing particle velocity in the range corresponding to particle velocities in plane progressive waves having sound pressure levels from 130 to 160 db.

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Normal incidence absorption coefficients were measured for a number of layer systems by conventional impedance tube techniques, adapted for high intensities, to determine the number of layers, layer spacing, and layer resistance suitable for the proposed room treatment. It was found that the goal of 96 percent absorption could be attained over nearly all of the frequency range from 50 to 7000 cps with systems of five to seven layers with irregular spacings and with normalized resistances per layer decreasing from values of about 0.6 for layers near the hard end (corresponding to the room surfaces) to values about 0.15 for layers at the incident sound side of the system. In spite of the fact that layer resistance increased with increasing particle velocity, it was found that variations in the normal absorption coefficients of the layer systems were small for measurements made at sound levels between 130 and 160 db.

Limited life tests at particle velocities corresponding to 160 db sound levels eliminated many materials for this high intensity application. Etched polyurethane foam and fine mesh wire screens were not damaged in this life test. This foam material, also called skeletal polyurethane foam was chosen as the recommended layer material because of its lower cost compared to multiple wire screens.

Specifications for a recommended layer treatment are given in Section VIII. This treatment consists of six layers of polyurethane foam supported by open mesh wire screen with spacings between layers ranging from 7 to 17 inches. A description is also given for an alternate treatment consisting of five layers which is less expensive than the six layer treatment but has a more irregular curve of absorption versus frequency. A suggested method is also described for supporting the layers so that the treatment can be collapsed into a relatively small volume for storage when the chamber is to be used for reverberant measurements.

SECTION II

CHOICE OF LAYER TYPE ABSORBING TREATMENT

Absorbing treatments for anechoic rooms for low intensity sound have generally used wedges of absorbing material (Ref. 2) (usually made of low density glass wool). This type of treatment has produced high absorption at frequencies above the cut-off frequency at which the depth of the treatment is equal to one-fourth wavelength. To attain low frequency absorption the wedges are long and must be supported by wire mesh or other means. The absorption of a wedge can be measured at normal incidence in an impedance tube, but, since the tube must include the base of the wedge, measurements can only be made at low frequencies, below that at which the tube cross section dimensions are less than a half wavelength. For a wedge with a one foot base the upper limit of measurement is about 500 cps.

Anechoic treatments using layers of absorbing material have also been built and performance tests have been reported by Bedel (Ref. 3). This treatment consisted of 16 layers of flannel and muslin, and absorption coefficients in the neighborhood of 98 percent were reported. The normal incidence absorption coefficient for this type of treatment can be measured over a wide frequency range in impedance tubes, since the normal absorption can be considered independent of area. The limitations on the cross section of the impedance tube are thus removed, i.e., a small diameter of impedance tube can be used at the high frequencies.

The decision to develop a layer treatment rather than a wedge treatment was made because of the following reasons:

(a) Measurement. As stated earlier, an upper limit on the frequency of measurement (about 500 cps) exists for wedges and this is not true for a layer treatment. It is also much more difficult to produce the required high intensities (up to 160 db) in an impedance tube large enough for a wedge. Measurements at the intensities specified are considered important because some acoustic properties of materials vary considerably at particle velocities corresponding to sound pressure levels of 140 to 160 db in a plane progressive sound wave.

(b) Collapsibility. One of the requirements for the treatment is the ability to be collapsed into a small volume when the ASD room is to be used for reverberant measurements. A collapsible wedge treatment would require the use of hollow wedges which could be collapsed by means of hinged members. In such a hollow wedge (Ref. 4), the absorbing material is attached to flat perforated sheets which are hinged so that the base width of the wedge can be shortened. Unless the absorbing material is compressed considerably, the width of the base cannot be reduced more than a certain ratio, estimated at about one-third. For a layer type treatment, the ratio of the collapsed volume to the extended volume can be made at least

as small as one-fourth (see Section VIII for a possible method of collapsing and storing).

(c) Absorption at Non-normal Incidence. Although the absorption of a solid wedge can only be measured accurately for normal incidence sound, wall treatments using solid wedges are effective at other angles of incidence. Spaced layer treatments can be expected to have reduced absorption at certain frequencies and angles of incidence where the layer spacing divided by the cosine of the angle of incidence (with respect to normal incidence) is equal to $n\lambda/2$. Hollow wedges which are required for a collapsible treatment will exhibit similar wavelength effects especially since they must be mounted with their hinged ends parallel.

For a layer treatment this effect can be reduced by using irregular layer spacing and low resistance for layers far from the wall. It is therefore expected that a well designed layer treatment will be satisfactory with respect to absorption at non-normal angles of incidence.

SECTION III

LAYER SYSTEM DESIGN

In the design of a layer type absorbing treatment the variables are number and spacing of layers and the acoustical impedance of each layer. The impedance of a thin layer can be considered as a lumped resistance except at high frequencies. For the high intensity application, layer material must be chosen to have the correct acoustical resistance at high sound levels and to be durable with respect to damage by sound and by handling during collapsing and storing. It must also be relatively unaffected by exposure to high humidity and temperatures between 0° and 250°F.

Although layer material qualities other than acoustical resistance are very important, the first steps in the design were consideration of the acoustical variables, with succeeding steps concerned with finding and testing materials having the required acoustical and durability requirements.

NUMBER AND SPACING OF LAYERS

The number of layers must be large enough to prevent wavelength effects from causing low absorption at certain frequencies. The absorptive effect of a thin layer will be small when it is located at a point where the sound particle velocity is small. A layer which is located at a distance of $n\lambda/2$ from a reflecting wall is at a velocity node in the standing wave of normal incident and reflected sound and the layer has little effect on the sound. For a small number of layers, there will be frequencies at which one or more layers are near velocity nodes and a significant decrease in absorption will result. A large number of layers can be located so that only a small proportion of this number will be located near velocity nodes.

Although many layers have acoustical advantages, the number must be minimized because of cost of the layers and their supporting structure, and the requirement that the treatment must be collapsed into a small space. Early in the program approximate calculations of the absorption of layer treatments were made and it was found that six layers gave a fairly smooth curve of absorption versus frequency. The method of calculation is described in Appendix II. The calculated results were confirmed by experimental results described in Section V. Six layers seemed a practical number from cost and mounting considerations and the dips in the absorption versus frequency curve were acceptable. Tests on five layer systems gave normal absorption curves which were nearly as satisfactory as those for six layer systems. Less than five layers would undoubtedly result in more and deeper dips in the absorption vs. frequency curve and more than six would become more expensive and difficult to support in a collapsible treatment.

The spacing of the layers in a system should be irregular to avoid the wavelength effects mentioned above. For instance, an equal spacing of 12 inches for 6 layers in the 6-ft treatment cannot be used without having low absorption at frequencies at which $n\lambda/2$ is 12 inches, 505, 1130 cps, etc. Small values of spacing cannot be used because of space requirements for mounting and collapsing. The minimum space between layers in the systems described in Section V was 7 inches.

In the neighborhood of 47 cps where $\lambda/4$ is six feet, layers near the wall are in the low particle velocity portions of the standing wave pattern and can be expected to have a smaller effect on the absorption than layers closer to the velocity maximum region. This reduction in effectiveness can be overcome to some extent by using layers with higher resistance near the wall.

LAYER IMPEDANCE (RESISTANCE)

Layer impedance in this discussion is defined as the acoustic impedance per unit area measured at the surface of a layer which is backed by zero impedance. This backing condition is approximated for measurement purposes (see Section IV) by mounting the layer at a distance of one quarter wavelength or odd multiples of a quarter wavelength from a hard end. When the layer thickness is small compared to a wavelength, the real part of the impedance is much greater than the imaginary part and the impedance can be considered to be a resistance. For layer thickness ℓ of 1.5 inch or less this approximation is good up to frequencies in the neighborhood of 1000 cps where ℓ/λ is about 0.1.

In calculating the absorption of layer systems it is convenient to use the normalized resistance R which is the acoustic resistance per unit area r divided by ρc, the characteristic impedance of air.

Calculations of the low frequency absorption characteristic of a six layer system (see Appendix II) showed that values of R for the layers should be in the range of about 0.05 to 0.5. A number of absorbing materials were then tested to find those with resistances in this range.

The materials which were tested are described in Table I which gives available specifications, surface densities and values of DC and AC resistances at particle velocities corresponding to 140 db.

In many cases the material specifications are not complete but more detailed specifications are given on those materials which are suitable for high intensity layer systems. The test methods and results are discussed in Section IV. Resistance to DC air flow is relatively simple to measure over a range of flow velocities and DC values give a fairly good indication of the AC resistance measured in a sound field with the same RMS particle velocity. The AC values, however, are approximately 1.5 to 2 times the DC values. Both R_{AC} and R_{DC} increase with particle velocity in the range corresponding to 140 to 160 db pressure levels in a plane progressive wave.

It was decided to design the layer treatment to meet the design goal of 96 percent normal incidence absorption coefficient at an intensity level of about 140 db. Although some areas of the ultimate treatment close to the siren sound sources may be exposed to 160 db sound, the greater part of the treatment will be at much lower levels. The calculated absorption values, however, did not vary materially for a range of acoustic resistance corresponding to a considerable range of intensity and this was confirmed by acoustic tube measurements of layer system at 130 to 160 db sound pressure levels. It is expected, therefore, that the 96 percent goal can be met for a wide range of sound intensity.

Layer systems with various combinations of layer spacing and resistance were measured in the impedance tubes. These tests, described in Section V, led to a preferred design from an acoustic standpoint. The choice of layer material is discussed in the following paragraphs.

LAYER SUPPORT

The materials to be used as layers have in general a low surface density and can be expected to vibrate under the influence of the sound pressure. This tends to change the layer impedance by decreasing the resistance and producing a mass reactance term that is appreciable at frequencies below 100 cps as outlined in Appendix II. It was difficult to check the magnitude of this effect in the impedance tube tests because the samples are only 3 inches in diameter and are clamped at their circumferences. The change in layer impedance can be calculated, however, for large areas exposed to sound at normal incidence. Calculated absorption coefficients for the preferred system are shown in Table II for a range of layer surface densities. Infinite surface density corresponds to no motion of the layers. It is seen that, above a surface density of 0.3 lb/ft^2, the effect of layer vibration is small. This can be attained by enclosing the light weight layer material between wire screens with an open area sufficiently large to have a negligible effect on the layer resistance. Such screens can form part of the layer supporting structure. Detailed design of the mechanical supports for the layer material was not in the scope of this project but a suggested method is described in Section VIII.

DURABILITY OF LAYER MATERIAL

The testing of layer material for durability under the action of intense sound requires accelerated life tests. Since the durability depends on the layer supporting structure as well as the properties of the material, a fairly large area of material should be tested under the same conditions of support as are to be used in the final installation.

Limited life tests on 3-inch diameter samples of layer material were made in the low frequency impedance tube and the test conditions and results are given in Section VI. The polyurethane material recommended in Section VIII withstood these tests without apparent damage, but some of the other materials failed after relatively short exposure to high intensity sound.

Accelerated life tests on a four by four foot specimen of layer material were made at 165 to 170 db in the discrete frequency, high intensity siren facility at North American Aviation, Columbus, Ohio. The polyurethane material showed only slight damage in a 105 hour exposure.

The material also performed satisfactorily in miscellaneous tests described in Section VII involving the effects of temperature, water absorption, etc.

SECTION IV

MEASUREMENT OF ACOUSTIC RESISTANCE

The acoustic impedance of a thin layer of material is defined as the ratio of the acoustic pressure at the surface to the volume velocity of air through the surface. As explained in Appendix II, the impedance of a material with zero impedance backing can be expressed as a function of the characteristic impedance, the propagation constant and the thickness. When the thickness is a small part of a wavelength (at low frequencies), the impedance is essentially a real quantity and can be considered as a lumped resistance. The resistance per unit area, r, often called the specific resistance, is the pressure divided by the linear or particle velocity. As mentioned previously, it is convenient to use the normalized specific resistance, R, which is $r/\rho c$ where ρc is 41.5 cgs units, the characteristic impedance of air. This definition of acoustic resistance can be extended to zero frequency or DC flow and this is termed R_{DC} to distinguish values measured by DC air flow from R_{AC} values measured in a sound field.

DC RESISTANCE TESTS

The flow measuring facility described in Appendix I was relatively simple to operate, and measurements over a range of air flow velocities were made on a large number of materials which are described in Table I. This was done in order to select materials for layer system tests. The results are shown in Fig. 1 (a) to (k). The normalized flow resistance R_{DC} is plotted against linear flow velocity. Use of a logarithmic scale for flow velocity allows the rate of change of resistance to be compared for materials having different resistances. The sound pressure level scale at the top of the scale represents the pressure levels of a plane progressive sound wave having RMS particle velocities equal to the flow velocities on the bottom scale. This relationship is shown in Fig. 2.

In general the resistance of a layer of material increased with flow velocity. Since the rate of increase varied considerably for different materials in the range of interest, 15 to 500 cm/sec corresponding to 130 to 160 db, no effort was made to fit a theoretical curve to the data. This could have been done by using an approximate relation (Ref. 5) between the resistance R and the flow velocity

$$R = R_o (1 + u/u_c) \qquad (1)$$

where u_c is the critical velocity at which R is twice the value of R_o, the resistance at low flow velocity.

As mentioned previously a considerable variation of resistance can be tolerated in the design of a layer system and materials must be selected for their durability rather than for precise resistance values at different sound levels.

Comparing the slopes of the resistance curves for different types of material shows that Fiberglas and glass wool in Figs. 1(c), 1(d), and 1(e) have a low slope in the region of interest and that wire screens in Figs. 1(f), 1(g) and 1(h) have slightly higher slopes. The slopes for polyurethane materials in Figs. 1(a) and 1(b) are greater than those for the wire screens and the slopes for woven glass cloth in Figs. 1(i), 1(j), and 1(k) are even greater.

Figure 1(h), showing the resistance of 1, 2, 3 and 4 layers of wire screen, is included to show that the resistance per screen is roughly constant so that desired resistance values can be obtained by multiple layers of screens. The tests also showed that the resistance was approximately proportional to thickness for the etched polyurethane foam material.

From the curves of Fig. 1, DC resistance values at the flow velocity corresponding to the particle velocity in a progressive plane wave with a sound pressure level of 140 db were obtained and listed in Table I. This tabulation enabled appropriate materials to be chosen for the tests on various layer systems.

AC RESISTANCE TESTS

The AC impedance per unit area of a thin layer of material was defined as the ratio of the sound pressure to the particle velocity at the surface of the material with zero impedance backing. At high intensities there are non-linear effects, since this ratio is not independent of particle velocity. An "average" impedance, however, was measured in the impedance tube at a particular frequency by filtering out the harmonics in the measured sound pressure. For convenience, this impedance is normalized by dividing by ρc (41.5 cgs units), the characteristic impedance of air.

To obtain zero impedance backing for a test sample, it was mounted at the end of the impedance tube and a hard end was located in the sample holder at a distance from the sample equal to an odd multiple of a quarter wavelength for the test frequency. At the sample location, there is a velocity maximum (pressure minimum) in the standing wave pattern and thus the impedance is small. With no sample, the measured impedance at this point was less than about 0.02 and was essentially real. With a sample in position, the imaginary part of the measured impedance was also very small for the thin samples tested and for frequencies below about 1500 cps. The real part of the measured impedance was taken as the AC resistance of the sample.

Tests were made over a range of particle velocities. It can be shown that the particle velocity at the velocity maximum is the same as the particle velocity in a progressive plane wave having the same pressure level as that measured at a pressure maximum in the standing wave pattern. The sound levels for the test results thus correspond to the pressure levels in a progressive plane wave having the specified test velocities at the sample.

Two spacings between sample and hard end were used, 67.8 inches for tests in the low frequency impedance tube at 50, 150 and 250 cps and 11.3 inches for tests in the medium frequency tube at 300, 900 and 1500 cps.

Five materials were tested, etched polyurethane foam No. 3 and No. 4, 100 mesh wire screen No. 5A, and glass cloth No. 1A and No. 4A. The results are shown in Fig. 3. DC resistance curves taken from Fig. 1 (shown as dashed lines) are included for comparison. In general R_{AC} is greater than R_{DC} and increases similarly with particle velocity.

Figures 3(a), 3(b) and 3(c) show the effect on R_{AC} caused by vibration of the test samples. As explained in Appendix II, the vibration of a light weight layer caused by the sound tends to reduce the AC resistance of the layer at low frequencies. The open symbols of Fig. 3(a) and 3(b) represent R_{AC} for a 3 inch diameter sample of polyurethane No. 3 clamped lightly at its circumference while the solid symbols represent R_{AC} for a sample supported on each side by two 20 mesh screens. While the effect of supporting screens can be attributed to an increase in surface density for large areas of material, the effect for the 3 inch diameter clamped samples in the impedance tube is complicated by resonant vibration of the samples. For example, in Figs. 3(a) and 3(b) the screens increased R_{AC} for the polyurethane by a relatively small amount at 50 and 150 cps but the increase was larger at 250 and 300 cps. In Fig. 3(c), the solid symbols represent R_{AC} for polyurethane No. 4 weighted by two discs of 1/4 inch mesh hardware cloth with diameters of about 2.5 inches.

When a sample was mounted at the end of the low frequency impedance tube so that its motion could be seen, considerable motion was observed and the displacement amplitude was a non-linear function of sound pressure level measured at a pressure maximum point in the impedance tube. The displacement at 100 cps increased rapidly with small increases in sound pressure at levels above 150 db. These non-linear effects are probably the reason for the different shape of the 150 cps curve in Fig. 3(a).

Although the tests on small unsupported samples in the impedance tubes were affected by sample vibration at low frequencies, values of R_{AC} for samples supported by screens are fairly representative of the performance of large areas of material with surface densities great enough to minimize vibration. The results show that

(1) R_{AC} increases with sound intensity at nearly the same rate as R_{DC}.

(2) R_{AC} varies with frequency but a meaningful average value can be assigned for frequencies between 50 and 1500 cps.

(3) The ratio R_{AC}/R_{DC} varies with material, from values in the neighborhood of 1.5 for etched polyurethane foam to values about 2 for wire screens and glass fiber cloth.

SECTION V

ABSORPTION OF LAYER SYSTEMS

NORMAL ABSORPTION COEFFICIENTS

The layer systems which were tested are described in Table III. It lists spacings of the layers, their thickness, surface density, the type of material in each layer, and the approximate DC and AC resistances at a particle velocity corresponding to 140 db. In this table, etched polyurethane foam material is abbreviated as PU and glass wool material as GW. More detailed information on layer material is given in Table I. The layers are numbered 1 - 6 with layer No. 1, the layer next to the hard end which simulates the wall or ceiling in the room treatment.

Most of the measurements in the impedance tubes were made on six layer systems since calculations had indicated that systems with fewer layers could be expected to have more irregularities in the absorption versus frequency curve. More than six layers would result in higher cost. Some tests were made later on five layer systems and one test on a seven layer system. Each layer system was assembled in the sample holder and measured in the impedance tubes to obtain standing wave ratios from which normal incidence absorption was calculated at each frequency. The results are given in Fig. 4 as curves of absorption coefficient versus frequency at various sound pressure levels.

Although measurements in the impedance tubes included the location of minima in the standing wave pattern from which the impedance of the layer system was calculated, the impedance is not given in the report. In general, the frequency regions where the absorption was low were characterized by an increase in the reactive part of the impedance.

Systems Nos. 1 and 2 were tested to check the performance of systems with tapered spacings and constant resistance per layer against values which had been calculated (see Appendix II). The curves of Fig. 4(a) and (b) for these systems show fairly high values of absorption below about 300 cps but were irregular at higher frequencies. System No. 2 was the mirror image of System No. 1 and had less irregularity at the higher frequencies. Because the irregularities in the curves produced undesirable absorption characteristics, measurements were not extended to frequencies above 2000 cps. The curves shown in Fig. 4(a) and (b) represent values measured at a sound pressure level of 140 db except for frequencies below 50 cps. Measurements were also made at 130, 150 and 160 db at a number of frequencies. The results (not shown for this system) indicated that the absorption was not greatly affected by sound intensity.

In system No. 3, the resistance per layer was "tapered" in three steps from higher values for layers 1 and 2 close to the hard end to lower values for layers 5 and 6. The spacing was the same as that for system No. 1. The tapered resistance improved the absorption curve compared to the curve for system No. 1 and, between 60 cps and 4500 cps, there was only one dip in the curve (at 475 cps) where the absorption was below the 96 percent criteria. Absorption measurements made on this system at different sound levels are shown in Fig. 4(d). The solid line was taken from the 140 db values of Fig. 4(c) and values for other sound levels are rather close to this line. Although the resistance of the layer material varies with sound level as was shown in Figs. 3(a), (b), and (c), there was little difference in measured absorption of the system. The fact that the absorption of this and other layer systems was not greatly affected by moderate changes in layer resistance is important because 1) the final room treatment will be effective over a range of sound pressure levels and 2) specifications for the resistance of materials in the final room treatment can be written with a reasonable tolerance for variations in this characteristic.

In system No. 4 the tapered spacing of system No. 3 was reversed so that the larger spacings were near the hard end. The absorption curve shown in Fig. 4(e) was also quite satisfactory. The absorption at 150 db is seen to be nearly the same as at 140 db.

In constructing a layer system for the room treatment, equal or nearly equal spacing would have advantages. System No. 5 having equal spacing of layers (12", 12", etc.) and system No. 6 having nearly equal spacing (14", 10", 14", etc.) were, therefore, measured to determine the magnitude of the dips in the absorption curve for frequencies at which layer spacing is approximately a whole number of half wave lengths. The curves of Fig. 4(f) for equal spacing have very low absorption at 525 cps and 1050 cps. For Fig. 4(g) with nearly equal spacing, measurements were made only in the medium frequency tube. The data are plotted as circles to be compared with the curve from Fig. 4(f) for equal spacing. The minimum at 525 cps was 81 percent for nearly equal spacing compared to 73 percent for equal spacing and the minimum at 1050 cps was nearly eliminated by the variation in spacing. The absorption curve for the nearly equal spacing is considered to be definitely inferior to the curves for layer systems with considerable variation in spacing.

There are advantages in the cost of layer systems having the same material and thickness per layer. Tests were therefore made on systems having equal resistance per layer and with the spacings of system No. 3. The results for three systems, No. 7 with $R_{DC} = 0.16$, No. 1 with $R_{DC} = 0.37$, and No. 8 with $R_{DC} = 0.7$ are shown in Figs. 4(h), 4(i) and 4(j) as circles joined by solid lines for comparison with the dashed line curve of system No. 3 which had tapered resistance. The measurements were confined to the frequency range of the medium frequency tube since this range provided adequate comparison of irregularities in the absorption curves. In all cases the absorption curves of systems with equal resistance per layer were more irregular than the curve for the system with tapered resistance. In the limited frequency range of the tests, the irregularities in the curve make it difficult to determine the best resistance per layer for such systems.

In Fig. 4(k) results are shown for system No. 9 which has tapered resistance as in system No. 3 but has a measure of randomness in layer spacing. The curve, however, was not much better than that of system No. 3.

Layer system No. 10 had tapered resistance per layer and a "random" spacing differing from system No. 9. An absorption curve for this system, Fig. 4(ℓ), was made for the extended frequency range. This curve exceeds the 90 percent criterion over nearly the whole frequency range.

In tests on layer systems in the 3 inch impedance tubes, each layer consisted of a 3.5 inch diameter disc clamped between spacers, 3 inch I.D. and 3.5 inch O.D. (see Fig. 16, Drawing of Sample Holders). With this boundary condition, vibration of a layer due to the sound field is quite different from the vibration of an equivalent area of material in the system to be used as a room treatment. The vibration of a layer with low surface density causes a change in layer impedance at low frequencies and this will affect the absorption of the system as explained in Section III and Appendix II. In the recommended treatment it is planned to support the layers between wire screens partly because the increase in surface density is desirable acoustically (especially for large areas of treatment) and partly because such support is desirable mechanically. It was decided to make tests on the system No. 10 with layers weighted with wire screens so that the surface density was in the same range as that for layers in the recommended treatment.

Discs of 1/4 inch mesh hardware cloth were attached on each side of each layer of system No. 11 by sewing through the layer material with thread. The 2.5 inch diameter of the screen discs was small enough to prevent contact with the clamping spacers so that they provided mass loading with little stiffening effect on the layers. Although the experimental system with weighted layers still did not simulate a system with large areas of material, the weighting reduced the resonant frequencies of the layers compared to the layers of system No. 10 and extended the lower limit of the frequency range where layer motion can be considered insignificant.

The results of tests on system No. 11 are shown in Fig. 4(m). Measurements were not made in the high frequency impedance tube since weighting of the 0.76 inch diameter samples would have been difficult and because weighting effects are small at high frequencies. Comparing the absorption curve for system No. 11 with that of system No. 10 with unweighted layers, it is seen that the curves are nearly alike except at frequencies near 700 cps. Although resonance effects in the weighted and unweighted layers must have been quite different, there was little difference in the measured absorption of the system. It is concluded that layer vibration had little effect on the measured absorption of these two systems in the impedance tube.

Subsequent to the development of the layer system discussed previously, it was reported that mechanisms for collapsing the ceiling treatment would require a clear space of two to three feet between the ceiling and the first layer. Information that this space (which is larger than that previously used) was not required was not received until the end of the program and tests were made on the remaining systems with layer no. 1 spaced 20 or 30 inches from the hard end.

Systems No's. 14 and 15 were six layer systems with random spacings and had a 30 inch space between layer no. 1 and the hard end. The test results shown in Figs. 4(n) and 4(o), were satisfactory, in that the normal absorption was above 96 percent except for narrow dips near 600 and 700 cps. The overall thicknesses of these systems was seven feet. This is greater than the six foot requirement but the extra thickness was not considered to be a serious handicap for the ceiling treatment. With six layers in a 42 inch space (72 - 30 inches) and a minimum clear space between layers of six to seven inches, it is difficult to obtain sufficient irregularity in spacing.

A number of five layer systems were designed and tested to determine whether they would be significantly inferior to the six layer systems. In systems No's. 16 to 19, inclusive, the resistance per layer was tapered in the same way as system No. 11 but the high resistance layer no. 1 was omitted. Systems No's 16 and 17 with 30 inch spacings to the hard end shown in Figs. 4(p) and 4(q) were inferior to the better six layer systems, although system No. 17 was close to the 96 percent criterion except for a deep dip (81 percent) at 700 cps. Systems No's. 18 and 19 with 20 inch spacing to the hard end shown in Figs. 4(r) and 4(s) were also inferior.

It was decided to retain the high resistances of layers 1 and 2 and reduce or change the taper of the resistances in layers 4 and 5. System No. 20 with only one layer, no. 5, with R_{DC} equal to 0.07 gave the fairly satisfactory absorption curve shown in Fig. 4(t). System No. 21, with a less abrupt change in resistance between layers no's. 4, 5, and 6, gave results shown in Fig. 4(u). Both of these systems had a 30 inch space between layer no. 1 and the hard end. Systems No's. 22 and 23 had hard end spacings of 20 inches. System No. 23 had tapered resistances as in systems No's. 20 and 21 but system No. 22 had a lower resistance for layer no. 2. Curves of absorption in Figs. 4(v) and 4(w) showed that system No. 22 was better than system No. 23 and was comparable with system No. 21.

Absorption curves for the five layer systems had more irregularities and deeper dips than the curves for six layer systems (compare Figs. 4(u) and 4(v) for five layer systems with Figs. 4(n) and 4(o) for six layer systems). A six layer treatment was therefore recommended although a five layer treatment was given as an alternate choice because of its lower cost.

Since the absorption of six layer systems was quite satisfactory, only a few tests were made on seven layer systems. Figure 4(x) shows these absorption curves for a seven layer system, No. 24. It is seen that this curve is smoother, except for the dip at 800 cps, than the curve for the recommended six layer system No. 11 shown in Fig. 4(m). The dip at 800 cps could probably have been avoided by a change in layer spacing, but it was decided that the improvement in absorption for a seven layer system compared to a six layer system was not worth the cost and mounting difficulties associated with the extra layer.

RANDOM ABSORPTION COEFFICIENTS

Previous measurements on layer systems were confined to normal incidence absorption coefficients. Wall and ceiling treatments in the ASD room will be exposed, however, to sound at various angles of incidence and there was a question whether wave length effects would decrease the absorption for certain frequencies and angles of incidence. Although this effect was not considered to be large because of the random spacing of the layers and the "tapering" of the resistance per layer, it was desirable to measure its magnitude. There are, however, many experimental difficulties in measuring absorption at a surface as a function of angle although this might be done more easily for the large surfaces in the completed ASD room. It was, therefore, planned as part of the supplemental agreement to measure random incidence coefficients for a section of a layer system in the reverberation room at the Riverbank Acoustical Laboratories. In a random field, sound energy is directed at a surface equally from all directions and low absorption at certain angles would tend to produce low random absorption coefficients. The test also provided experimental data on a fairly large area of a layer system with supports (wire screens) similar to those of the recommended treatment. Thus, data on the 3 inch diameter areas previously measured could be checked.

The specimen tested was 62 by 76 inches in cross section and consisted of the polyurethane foam layers and spacings of system No. 11. Each layer of polyurethane foam was mounted between wire screens which were clamped at their edges in wood frames. The wood frames were mounted in a box of 3/4 inch plywood 69 by 83 inches in cross section and 6 ft. long with layer No. 6 located at the open end. The box was mounted in an opening in the reverberation room wall so that layer No. 6 was part of the wall and was exposed to the random sound field.

Conventional tests of absorption at Riverbank are made on 8 by 9 ft. samples at frequencies of 125, 250, 500, 1000, 2000 and 4000 cps which are warbled $\pm$ 20 cps five times per second. The time for a 40 db decay of sound is measured in the room first with and then without the sample by two separate microphone systems and the absorption is calculated from the difference in decay rate caused by the absorption of the sample. There is a statistical variation in the measured times so that 50 to 100 readings are taken for each decay time.

The layer system sample was measured in the conventional way and additional measurements were made at intermediate frequencies with a single microphone system and adjustable filters. There was time to make only 20 to 40 readings for each room condition at these intermediate frequencies and the absorption coefficients are therefore not as accurate as those for the conventional frequencies.

The results are shown in Fig. 5 plotted on the same scale as the results of normal incidence measurements. This scale, however, exaggerates the accuracy of the data as is explained below. In the interpretation of the curve, comments should be made not only on the accuracy of the coefficients but also on the coefficients which exceeded 100 percent. As explained previously, values at the usual frequencies of 125, 250, 500, 1000, 2000 and 4000 cps have less measurement error than those at intermediate frequencies, but error was introduced in all measurements by the small size of the absorbing specimen, approximately 33 sq. ft. compared to 72 sq. ft. for a conventional test specimen. For example, the absorption of the room without the test specimen is about 125 sabins at 500 cps and the room with the sample (assuming 100 percent absorption) would be 158 sabins. The accuracy of the specimen absorption, therefore, depends on small differences between large quantities. The measurements at 100, 125 and 150 cps have further sources of error since they were near the frequency range where a room of this size does not have a random sound field.

With regard to absorption coefficients over 100 percent, such values are commonly measured in reverberation tests on highly absorbent samples of small size. Due to diffusion at the edges of an absorbing area located at a reflecting surface, the effective area of the sample may exceed the actual area. Thus, the sample of 33 sq. ft. might have an effective area of 40 sq. ft. and result in a measured absorption of about 40 sabins giving an absorption coefficient of 120 percent.

Corrections for this edge effect have not been agreed upon by various laboratories because the theory has not been satisfactorily worked out. Some laboratories routinely reduce all values above 100 percent to 99 percent. In others, corrections are applied depending on the magnitude of the measured absorption and the frequency and are based on tests on large areas of material.

With these qualifications in mind, the following conclusions are drawn from the data of Fig. 5.

1. **The 33 sq. ft. area of layer system No. 11 had random absorption coefficients greater than 96 percent over most of the frequency range between 200 and 4000 cps. The data thus substantiates the measurements of normal absorption coefficients made on the 3 inch diameter areas.**

2. The low values at 100 and 125 cps probably are the result of measurement error.

3. Wave length effects leading to low absorption were not of sufficient magnitude to be detected except perhaps at the narrow dip at 860 cps.

4. The width of this dip is small so that it should not interfere seriously with tests in the ASD facility.

SECTION VI

FATIGUE TESTS ON LAYER MATERIALS

The durability of a layer treatment depends on the supporting structure for the absorbing layers as well as the layer materials. Tests should therefore be made on layers large enough in area to simulate types of layer supports to be used in the final installation. Since extended life tests are expensive and time consuming, it was decided to select materials on the basis of small area tests of relatively short duration made in the impedance tube facility. Larger specimens of material which withstood exposure to 160 db sound in the impedance tube could then be exposed for extended periods at higher sound levels.

LIMITED LIFE TESTS

The limited life tests on small areas consisted of exposure of 3 inch diameter samples of material to particle velocities equal to the velocities that would occur in a progressive plane wave at 160 db. The samples were mounted as in the AC resistance tests at a distance equal to one quarter wave length from a hard end. The test frequency was 100 cps and the spacing from the hard end was 33.8 inches. This frequency was chosen because adequate power was available from the sound sources without danger of failure and because the displacement amplitude of vibration was over 0.5 inches for etched polyurethane foam no. 3 (without wire screen supports), one of the materials recommended in the preferred layer system. It is believed that such large displacements of an unsupported layer would provide an accelerated life test, since considerably smaller displacements are expected for supported layers.

Failure occurred for two materials during routine impedance tube tests for the measurement of acoustic resistance or layer system absorption. Fiberglas PF 334, used in systems No. 1 and No. 2, failed during system absorption tests at low frequencies. The material of layer No. 6 (see Fig. 4) was torn as is shown in Fig. 6(a) and fibers were observed on the inside surfaces of the impedance tube and sample holder close to this layer. The failure of this type of material after relatively short exposure is considered a sufficient reason for eliminating low density glass fiber materials at least in the layers exposed to high sound intensities. No changes in this material were observed, however, which could be attributed to high temperatures.

A sample of Fibermetal failed during AC resistance tests at 50 cps. The damage can be seen in Fig. 6(b). Although this material can be made with various sizes of fiber and sintering conditions, it is not considered suitable because the low flow resistance specifications for layer treatments require a low density and thickness and, therefore, a low strength for the material.

A sample of etched polyurethane foam, material no. 3, was run in the limited life test setup at 100 cps and 160 db for three hours without any damage which could be observed visually. This sample had previously been exposed to 157 db at 50 cps for three hours. Another sample of this material was exposed for three hours to 160 db at 100 cps and the DC flow resistance was measured before and after the test. There was no change in measured flow resistance within the 1 to 2 percent accuracy limitations of the measurement.

Two samples of glass cloth material no. 8 were tested. The first sample showed a shifting of the strands toward the center of the disc and considerable fuzzing of the fine fibers in the strands in the exposed area. This occurred in the first two minutes of the 10-minute test. A second sample was exposed for an hour without tearing or breaking and the amount of fuzzing did not increase noticeably after the first ten minutes. The displacement amplitude of vibration was about 0.5 inches. A photograph of this sample is shown in Fig. 6(c). It is reasonable to eliminate this type of material in designing high intensity layer treatment on the basis of the rapid changes which occurred in the test.

A limited life test was made on a sample of 100 mesh wire screen material no. 5 clamped at the end of the low frequency tube in the same way as the woven glass cloth. No damage could be seen at the end of a two hour exposure to 160 db at 100 cps.

No effects which could be attributed to a temperature rise due to the sound were observed in the limited life tests or in other tests at sound levels up to 160 db. Damage due to temperature in a layer system probably is greatly reduced by the fact that only part of the incident sound energy is converted to heat in each layer. The lower resistance of layers 5 and 6 tends to reduce the energy absorption in these layers.

EXTENDED LIFE TESTS

A sonic fatigue test was made in the discrete frequency high intensity siren facility of North American Aviation, Inc., Columbus, Ohio on a four by four foot test specimen of 1/2 inch etched polyurethane foam material no. 3, 60 pores per inch, mounted between 2 mesh stainless steel wire screens. A reproducible copy of the report on this test prepared by North American Aviation has been submitted to the sponsor.

The test specimen was mounted in a square aluminum frame which clamped the edges of the wire screens enclosing the foam material and which was bolted to the siren facility. Figure 7 shows details of the mounting frame and Fig. 8 is a photograph of the specimen installed in the siren facility.

The screens, which were approximately 56 by 56 inches in size, were clamped between the 1/2 inch outer members and the 3/8 inch spacer member. The foam material, 48 by 48 inches in size and 1/2 inch thick, was compressed by the screen to a thickness of 3/8 inch at its peripheral edges. The foam material was in three pieces, one 4 by 2 feet for the upstream half with the four foot edge vertical and two 2 by 2 foot pieces for the downstream half. The screens were laced together at eight places along the junctions of the foam pieces and at the center of one of the 2 by 2 foot pieces as is shown in Figs. 8 and 10. The circles in Fig. 10 represent bolts through thin dished washers, 1 inch in diameter and the short diagonal lines represent wire lacings.

One side of the specimen formed part of the wall of the rectangular exhaust passageway of the siren with theupstream edge 16 inches from the siren horn assembly and the other side of the specimen was enclosed by aluminum close out plates approximately 4 inches from the foam material.

Three test frequencies were chosen to correspond with peaks in the acceleration versus frequency curves taken at 160 db sound pressure level. The four accelerometers were mounted at (1) top center, (2) middle of downstream top quarter, (3) middle of panel, and (4) middle of downstream half. Gulton Industries Model A322 accelerometers were used and they were cemented to the wire screens during this part of the test. Although the acceleration amplitude varied with location of accelerometer the curve of Fig. 9 is fairly typical with regard to variations with frequency. Test frequencies of 140, 365 and 625 cps were chosen to correspond with peaks in the curves. A 35 hour life test was run at each frequency and inspections of the specimen were made at one hour intervals during the first three hours of a test and at four hour intervals thereafter. Sound pressure levels were monitored by three microphones in the siren air streams along the horizontal center line of the specimen, one being near the upstream edge of the specimen, one at the center and the third near the downstream edge. A fourth microphone was used to monitor the sound pressure level at the center of the specimen near its outside surface during periods when the microphones in the exhaust air stream were fouled by water, oil, etc.

In Test No. 1 at 142 cps, the sound pressure levels were 166 db upstream, 164 db center, and 167 db downstream. No damage was observed during the 35 hour test, other than the loss of a lacing bolt which was replaced. At 23 hours, a malfunction of the siren lubrication system caused oil to be sprayed on the specimen and at 35 hours it became oil soaked.

In Test No. 2 at 365 cps, the sound pressure levels were 166 db upstream, 167 to 169 db center and 163 downstream with the higher levels corresponding to the period between 21 and 35 hours. At the end of 2.5 hours, the siren air drying system failed and the specimen was sprayed with water and ethylene glycol in addition to the oil spray mentioned previously. It was decided to continue with the now thoroughly soaked specimen and the test was resumed after mopping out the siren exhaust passage. Following this, the oil spray was reduced to a minimum. There was no damage to the specimen during this 35 hours test except for the loss of lacing bolts which were replaced by bolts with lock type star washers.

In Test No. 3, there were numerous siren breakdowns in the first three hours of operating time at 625 cps and in the remaining period a frequency of 640 cps was used. Sound pressure levels were 168 db upstream, 167 db center and 158 db downstream. At the end of 8 hours, breaks in the screen wires were observed and "square pattern" cutting of the polyurethane. The specimen was dismantled and 48 breaks were observed in the inside screen (toward the exhaust passage) and 31 breaks in the outside screen. There were many breaks at and close to the clamping edges and breaks along a horizontal line a few inches above the center line of the specimen. The locations of the breaks in the wire screen are shown in Fig. 10. The damage to the polyurethane consisted of slightly ragged cuts where it was in contact with the screen and extended from 2 inches to 8 inches from the upstream edge of the specimen. These "square pattern" cuts were deepest (about 1/16 inch) near the upstream edge.

New screens were installed but the same polyurethane foam material was used in the remainder of the test, 27 hours. The contact pattern of the new screens on the polyurethane was slightly displaced from the pattern of the old screens. There was no indication of damage to the wire screens during the remaining 27 hours of the test and the damage to the polyurethane material consisted of square pattern marks or very shallow cuts near the upstream edge.

Tentative conclusions from the accelerated life tests are that the screen failure was mainly the result of the 78 hour cumulative time of exposure rather than the 8 hours exposure in Test No. 3. Although Test No. 3 at 625 cps may have been more severe, the new screens were not damaged by 27 hours of exposure at this frequency. Although the damage to the polyurethane material was not observed until 78 hours of exposure, it probably occurred earlier. It may not have been noticed because the cuts were hidden by the wires. This type of damage was very small in the final 27 hours of exposure in Test No. 3. In general, the specimen stood up very well under adverse conditions of oil and water soaking in that major damage to the screens did not occur until about 78 hours of exposure; the damage to the polyurethane foam was small for this exposure time. It is understood that further accelerated life tests may be made at ASD after analysis of the specimens used in the North American tests. A cheaper screen material can possibly be used on the basis of such tests.

SECTION VII

MISCELLANEOUS TESTS ON POLYURETHANE FOAM

A series of tests was made to determine characteristics and performance of etched polyurethane foam, 60 pores per inch, with relation to the effects of vibration, high humidity and temperature. The results of tests on 1/2 inch thick samples of material are summarized below.

Exposure to a sound pressure level of 160 db at 100 cps for three hours at vibration amplitudes of about 1/2 inch caused no measurable change in DC flow resistance.

Three cycles of exposure to a temperature of 40°F and then to 100°F with a relative humidity exceeding 90 percent caused a negligible increase in sample weight (less than one percent). This showed that condensation of water vapor in the pores of the material was very small under these conditions.

Soaking in a 10 percent solution of acetic acid for five hours caused a weight loss of less than five percent (acetic acid is reported to be an agent for etching this material).

When a rectangular piece of the foam material was soaked in water and was then held with a half inch edge horizontal, the water drained out rapidly except for an area close to the bottom edge. Rotating the piece about a horizontal axis caused much of this remaining water to drip out of the corner. With this type of drainage, water will be retained in the layer material only near a horizontal edge. It will, therefore, be desirable to avoid cemented butt joints which will be horizontal in the installed layers.

Temperature effects on the foam material have been the cause of some concern. The melting point is about 475°F and the manufacturer recommends use up to 250°F. The material has been used, however, in commercial applications for long periods at 375°F. A sample of material exposed in an oven for three hours at 250° showed no measurable change in weight or DC flow resistance.

The tests described above indicate that damage to the polyurethane foam would not be caused by ambient conditions in the room involving maximum temperatures of 250°F and maximum relative humidity up to 100 percent. Temperatures in the material which are higher than ambient room temperature are expected, however, because of the conversion of acoustical energy into heat. Portions of the treatment located near the sirens will be exposed to an acoustic intensity of about one watt / cm^2 (for a plane progressive wave with a 160 db sound pressure level).

An unknown portion of this acoustic energy is absorbed in the various layers. We can, however, estimate the energy loss in layer 6 (toward the room interior) from the particle velocity at its surface and its acoustic resistance. The RMS particle velocity u in the progressive wave in terms of the RMS sound pressure p and the characteristic impedance ρc is

$$u = p/\rho c \tag{2}$$

and the energy loss per unit area, E_6, in layer No. 6 with an acoustic resistance of r_6 is

$$E_6 = u^2 r_6 \times 10^{-7} = (p/\rho c)^2 r_6 \times 10^{-7} = p^2 R_6 \times 10^{-7}/\rho c \tag{3}$$

Substituting $p = 2 \times 10^4$ dynes/cm^2 for 160 db SPL, $\rho c = 41.5$ grams/cm^2 sec and $R_6 = 0.13$ from measured values for 1/2 inch polyurethane faom, 60 pores/inch, gives E_6 as approximately 0.14 watts/cm^2. The energy dissipated in succeeding layers cannot be conveniently estimated because the particle velocity decreases at an unknown rate toward the wall.

The temperature in the layer material also depends on the rate of heat flow to the air adjacent to it and thus on the heat flow conditions in the air between layers. These heat flow conditions were difficult to simulate in small scale experiments involving the impedance tube as a sound source, but the following two types of tests were made to obtain temperature information.

1. A layer was mounted at the end of the impedance tube and backed by a quarter wave length air space so that the particle velocity at its surface could be determined by measurements in the impedance tube. The air space was enclosed by a glass tube which was wrapped by a two inch layer of fiberglas. Temperatures were measured by three thermocouples, one imbedded in the material at the center of the layer, and the others on either side at a distance of three inches from the layer surface. This test was designed to produce high temperatures in the insulated air space in the glass tube within a relativelv short time and to determine differences in temperature between the material and adjacent air spaces.

2. Layer system No. 11 was mounted in the steel sample holder which was insulated with a two inch layer of fiberglas. Temperatures were measured by means of four thermocouples, one imbedded in layer No. 6 (at the end of the impedance tube) and the others in the air spaces between layers No. 5 and 6, 4 and 5, and 3 and 4. This test was designed to

determine temperatures in air spaces of different sizes for a layer system. Approximate temperatures in the layers can be estimated from differences in temperature between material and air space in other tests. Heat flow from the air space perimeter was through the 1/4 inch thick steel spacers, 3 inches inside diameter, which were fitted into the 1/4 inch thick tube of the sample holder. Heat flow to adjacent air spaces through the steel tubes was probably small in comparison to the heat flow through the porous layer materials because of the low conductivity of steel.

The results of tests on a 1/2 inch layer of polyurethane foam, 60 pores per inch, with a quarter wave length backing are shown in Figs. 11 and 12. The upper part of Fig. 11 shows temperature rises for 160 db SPL which were measured at pressure maximum points in the impedance tube. The temperature in the material approached a value near 150°F while the temperature in the insulated glass tube three inches from the layer approached 130°F. In the impedance tube the temperature approached a value of about 113°F. The curves show a rapid increase in temperature at the start of the test and this is typical for all the temperature tests. The lower part of Fig. 11 shows temperatures for a 157 db SPL in the impedance tube. The asymptotic values of temperature were approximately 134°F in the material, 117°F in the glass tube, and 105°F in the impedance tube.

Previous temperature tests at 160 db on this material near 100 cps gave steady state temperatures from 120 to 210°F for tests at frequencies of 99 cps and 103 cps respectively. It is believed that vibration of the polyurethane material was associated with these variable results since there was a resonant peak near 100 cps. The 3 inch disc of polyurethane had been weighted with discs of 4 mesh hardware cloth and the addition of solder to these weighting discs produced the more consitent results of Figs. 11 and 12.

Because of damage to the cones of the loudspeakers caused by testing for several hours at 160 db, it was decided to make further tests at 157 db. Figure 12 shows results of tests at 157 db at frequencies of 200 and 400 cps on the same 1/2 inch layer used for Fig. 11. The temperature rises in the material were about the same at 200 cps, 135°F, but were considerably higher at 400 cps, 170°F.

The reason for the increase in temperature with frequency may be partly due to an increase in acoustic resistance of the layer material or it may be associated with the smaller particle displacement at higher frequencies which would tend to transfer heat less rapidly to the air adjacent to the material. The temperature in the glass tube was about 17°F below the temperature in the material for 100 and 200 cps and about 28°F below the temperature in the materail at 400 cps. The temperature in the impedance tube approached about 105° at all three frequencies.

Tests at 108 and 590 cps and 160 db on layer system No. 11 are shown in Fig. 13. In this test condition a rapid rise in temperature occurred at the start of the test followed by a slow change for a long period, presumably caused by the large heat capacity of the steel walls of the sample holder. These tests showed higher temperatures at 590 cps than at 108 cps

both in layer No. 6 and in the air spaces between layers. The rate of heat flow into and out of the air spaces is affected by various factors, mentioned previously, which are difficult to estimate as well as the following known conditions. The space between layers 5 and 6 was 17 inches long and was terminated by 1/2 inch layers of foam, 60 pores/inch. The space between layers 4 and 5 was 7 inches long and was terminated by layer 5 (1/2 inch, 60 pores/inch) and layer 4 (1 inch, 80 pores/inch). The space between layers 3 and 4 was 15 inches long and was terminated by layers of foam (1 inch, 80 pores/inch). On the basis of heat conduction to the sample holder only, one might expect that the 7 inch air space between layers 4 and 5 would reach higher temperatures than the other two spaces, 17 and 15 inches in length. This was true at 108 cps but at 590 cps the temperature of this space was equal to the temperature in the space between layers 5 and 6 presumably due to the high temperature in layer 6. The temperature in the space between layers 3 and 4 was fairly low at both frequencies, indicating small energy losses in the adjacent layers. This, however, might not occur at other test frequencies.

Conclusions to be drawn from the temperature tests which are applicable to conditions in the large scale facility must be tentative in nature. The following results may have bearing on the problem.

1. The tests on 1/2 inch polyurethane, 60 pores/inch, with a quarter wave length backing having considerable heat insulation, produced temperatures in the material in the neighborhood of 200°F for particle velocities corresponding to 160 db SPL in a plane progressive wave. Room temperature was 70°F to 80°F.

2. The differences between temperatures in a layer and in air spaces adjacent to it were about 15 to 30°F for a single layer backed by a well insulated air space (glass tube) and 30 to 70°F for a layer system with less well insulated air spaces (impedance tube).

3. Temperatures in the air between layers of a particular layer system (system No. 11) varied with position of the air spaces.

4. It is inferred that higher temperatures occur adjacent to layers far from the hard end (room surface) at higher frequencies and there is more uniform distribution of temperature throughout the treatment at lower frequencies.

With regard to possible damage to layer material due to high temperatures, the following two points should be considered. The first is that excessive temperatures can only occur in relatively small areas near the sound sources where the sound pressure level is close to 160 db and will probably be confined to layers No. 4, 5 and 6. The second is that the temperature between the first few layers in these locations can easily be monitored by thermocouples when the ASD room is first tested and provision can be made for moderate amounts of air circulation if it is required.

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

As a result of the research concerning the design of an absorbing treatment for the ASD high intensity test chamber, certain conclusions are drawn related to the acoustical effectiveness, durability and practicality of a layer type treatment and tentative recommendations for a preferred system are given in the following paragraphs.

CONCLUSIONS

The conclusions listed below are based largely upon the results of impedance tube tests but it is believed that they are valid for a large scale absorbing treatment for the ASD chamber.

1) A system of spaced layers can be designed to provide a normal absorption coefficient of 96 percent or better, from 50 - 10,000 cps, for the ASD chamber.

2) The absorption coefficient of such a system will not vary materially for incident sound with sound pressure levels between 130 and 160 db.

3) Tolerances on the acoustical properties of layer materials are wide enough to permit the use of relatively low cost commercially available material.

4) The spacing of layers is not critical so that reasonable tolerances can be given for the mounting of layer material.

5) The fact that a 4 by 4 foot specimen of a layer of etched polyurethane foam mounted between wire screens withstood over 70 hours of exposure to sound pressure levels from 165 to 170 db without damage indicates a long life for the layer treatment at a maximum of 160 db sound pressure level. Temperature effects in the layers due to the intense sound were not well simulated in the extended life test, however, and limited tests on layer treatments with restricted air circulation between layers indicate that layers close to the sirens may reach temperatures over 200°F. Excessive temperatures can be prevented by air circulation in the space

between layers for parts of the treatment which are close to the sirens, if this is found to be necessary (see Recommendations).

6) Although the mechanical details of layer support and construction were not considered to be within the scope of the project, it is believed that system supports can be designed to permit convenient collapsing of the layer treatment into a reasonably small space for approximate reverberant conditions in the ASD chamber.

RECOMMENDATIONS

Tentative specifications for the layer treatment will serve as a basis for more detailed design with relation to mechanical construction, cost, durability and collapsibility. With regard to durability in the high intensity sound field, it is recommended that accelerated life tests be made on sections of layers of the final design which are several square feet in size.

Number and Spacing of Layers

The recommended layer system consists of six layers of absorbing material approximately parallel to the chamber walls or ceiling with spacings as shown for system 11. Fig. 4(m) and Table III (c). The clear distances between layers 1 to 6 are thus 11 inches (wall or ceiling to the first layer), 13, 9, 15, 7 and 17 inches respectively. Tolerances for these spacings may be as large as ± 0.5 inch with a greater tolerance, up to ± 3 inches for the space between the wall or ceiling and the first layer.

Acoustical Characteristics of Layers

The acoustical characteristics of the layers depend mainly on the acoustic resistances R_{AC}. Measured values at 140 db SPL are given in Table III (c) for system No. 11 as 0.66 for layers 1 and 2, 0.44 for layers 3 and 4, and 0.13 for layers 5 and 6. Tolerances for these values may be about ± 10 percent. Since acoustic resistance is difficult to measure to meet specifications, etched polyurethane foam might be specified with specified thickness and pore size as given below under layer material.

Layer Material

Two materials can be recommended from those tested for layer material for this high intensity application, etched polyurethane foam, also called skeletal polyurethane foam, and fine mesh wire screen. Since the polyurethane foam is considered satisfactory with regard to acoustical properties and the results of durability tests and is also less expensive than screens, it is recommended. This material is available commercially in a range of pore sizes and thicknesses. To attain the required acoustical characteristics, layers 1 and 2 can consist of 1.5 inch material with a pore

size of 80 per inch, layers 3 and 4 can be the same material one inch thick, and layers 5 and 6 can be 0.5 inch material with a pore size of 60 per inch. For this material, the specified acoustic resistances can be monitored by the equivalent DC flow resistances for each layer which are quite easily measured, and which are given in Table III (c) for system No. 11 at a flow velocity of 50 cm/sec. It is understood that the manufacturer monitors pore size by means of a measurement of DC resistance, i.e. pressure drop across a given thickness and area for a specified air flow.

Surface Density

The surface density of the layers should be about 0.5 lb/ft^2 but tolerances can be as large as $\pm$ 0.2 lb/ft^2. For light weight absorbing material the required surface density can easily be obtained by supporting the material between open mesh wire screens. For example, aluminum or galvanized steel screens (hardware cloth) with a 1/4 to 1/2 inch mesh size will increase the surface density but will not affect the flow resistance of a layer. If a light weight netting is used to support the material, it will be necessary to attach closely spaced weights to prevent vibration.

Layer Supporting Structures

The mechanical requirements for layer supports depend to a great extent, on the method of collapsing and storing the treatment when the chamber is to be used for reverberant measurements. A suggested method is to divide each layer into framed panels about 10 by 10 feet in size. Each panel may then be subdivided into convenient sections of polyurethane foam, supported on each side by and laced to wire screen. Methods of enclosing the polyurethane foam and attaching the screens to the frames have not been worked out. Since both the screens and the foam are subject to acoustic fatigue which may be localized at the supports, various methods of attachment should be checked in accelerated fatigue tests.

For collapsing the treatment the arrangement shown in Fig. 14 is suggested. This is a photograph of a scale model showing the panels for six layers of ceiling treatment and for one layer of wall treatment. In the ceiling treatment, panels for the six layers are supported from the ceiling by four cables. The ceiling treatment extends to about six feet from the walls. The treatment is collapsed either by raising the panels to the ceiling for storage there or preferably by lowering them to the floor for removal from the room. The collapsed panels for the six layers will occupy a space 10 by 10 feet in area and about one foot in thickness.

The panels for each wall layer (see Fig. 14) are positioned by guide calbes anchored to both ceiling and floor. Two guide cables are required for each vertical system of panels. Each panel of a layer is located just back (toward the wall) of the panel above it so that the lower panels can be raised to a position behind and close to the top panel. Utilizing projecting members at the bottom of each panel, the panels can be raised to the ceiling by means of one or two hoisting cables. As the panels are lowered, projecting members at the top of each panel (except the uppermost) engage mating members at the bottom of the next higher panel. Consequently, each panel ultimately supports the next lower panel, the total load being supported by the uppermost panel which anchored to the ceiling. Since the travel is the same for all six layers, the hoisting cables can be attached to a single cable for operation by a winch. With this method, the collapsed wall treatment will occupy a space about 10 feet high by 6 feet thick along the upper perimeter of the chamber.

Under consideration for the wall treatment is another type of support for the absorbing material using a fabric netting (made perhaps of nylon cord) on each side of a layer so that the vertical layers would be flexible enough to be raised in loops or folds. Lacings through the absorbing material at close spacings might be designed to provide the required weighting without serious loss in flexibility. This type of flexible support will require checking for fatigue resistance.

Alternate Five Layer System

If it is desired to save the cost of one layer at the expense of slightly poorer performance, a five layer system can be recommended instead of the six layer system. Five layer system No. 21 is given as an alternate recommendation. The layer spacings and materials are given in Table III (e). The materials are the same as used in the recommended system No. 11 and the same specifications apply.

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APPENDIX I

DEVELOPMENT OF HIGH INTENSITY TEST FACILITY

Impedance tubes were designed to measure normal incidence absorption coefficient over a wide range of frequency and at high sound intensity. The design goal of 160 db intensity level for tests over the frequency range of 50 to 7,000 cps was substantially achieved in that measurements at 160 db could be made over most of this range. Measurements at lower intensities were possible down to about 20 cps.

Three impedance tubes were designed, a low frequency tube (3 inches in diameter and 20 ft long) for frequencies between 20 and 300 cps, a medium frequency tube (3 inches in diameter and 3 ft long) for frequencies between 300 and 2,000 cps, and a high frequency tube (0.76 inches in diameter and 15 inches long) for frequencies between 1500 and 6000 cps. These tubes were driven by high power sound sources and amplifiers and were equipped with movable microphones and measuring systems. Sample holders for convenient mounting of layer type absorbing systems were provided for each tube. The detailed description of the system and a discussion of design criteria are given in the following paragraphs.

In order to measure the DC resistance of absorbing materials for layer systems, the range of existing flow resistance equipment was extended for measurements at flow rates corresponding to the particle velocity of a plane wave at 160 db sound pressure level. This setup is also described below.

IMPEDANCE TUBES

A drawing of the low frequency impedance tube is shown in Fig. 15. The medium frequency tube is of similar construction. The high frequency tube is shown in Fig. 16. The low and medium frequency tubes were mounted in the center of plywood boxes of sand approximately 8.5 by 12 inches in cross section in order to damp resonant vibrations of the tube walls. The horn sections coupling the low frequency tube to the drivers was also damped by sand. The minimum thickness of sand at all surfaces of the tubes and horn was four inches and over 6000 lbs of sand were used.

The dimensions and frequency ranges of the low, medium and high frequency impedance tubes given in Table IV were determined in part by the characteristics of the sound sources and in part by the requirements related to sound wavelength. The diameter for the low and medium frequency tubes was 3 inches. A larger diameter would have some advantages with respect to reducing the effect of edge mounting conditions of the test samples but it would be difficult to obtain sound sources with enough acoustic power output to reach the required intensity level of 160 db. (Intensity level based

on 10^{-16} watts/cm^2 is numerically equal to sound pressure level based on 0.0002 dyne/cm^2 for a plane progressive sound wave in air.) The upper frequency limit for a circular tube is determined by the frequency for the first cross mode. This cut off frequency is given by Morse (Ref. 6, p. 308, Eq. 26.15) for a cylindrical tube as

$$f_1 = 0.586\ c/2a \tag{4}$$

where f_1 is the cut-off frequency, c is the velocity of sound and a is the radius of the tube. For a 3 inch tube the cut-off frequency is 2650 cps. This mode has a node at the tube axis and it is estimated that the effect on tube measurements is not significant at frequencies below about 2000 cps if the microphone is mounted at the tube axis.

The diameter for the high frequency tube was 0.76 inches and the cut-off frequency for the first cross mode was 10,500 cps. In this tube it was difficult to keep the microphone accurately on axis and the upper limit for measurements was about 7,000 cps.

The length of the low frequency impedance tube was set by the space available for the tube and its associated horn. The tube was 20 ft long, the horn with its coupling section was 16.5 ft long, and the sample holder was 6 ft 4 inches long, giving an overall length of about 43 ft. In the 20 ft tube length two minima in the standing wave pattern could be measured for frequencies above about 57 cps for any sample impedance. Below this frequency, measurements were in some cases restricted to one minimum point and one maximum with some loss in accuracy involved in calculation of the wave length and estimating the attenuation along the tube. The latter source of error was not very significant since the attenuation along the tube was small for the samples of high absorption which were measured.

The 300 cps upper frequency limit of the low frequency tube was determined by the driver characteristics. Above 300 or 400 cps there was "breakup" in the loudspeaker cones resulting in lowered acoustic output.

The length of 36 inches for the medium frequency tube allowed measurement of two minima in the standing wave pattern at frequencies above about 375 cps. In the range between 375 cps and the 300 cps, the lower limit of this tube, it was occasionally necessary to use measurements on only one minimum and maximum. The upper limit for this tube was about 2,000 cps because of cross modes as discussed previously.

The high frequency tube was 15 inches long and two minima could be measured for frequencies above 900 cps. A low frequency limit of about 1500 cps was set by the driver characteristics. As discussed previously, the upper limit for this tube was about 7000 cps because of cross mode effects.

The sound field inside each impedance tube was explored by a microphone mounted inside the impedance tube at the end of a probe tube. A tube was used instead of a rod in order to provide a shielded conduit for the microphone cable. The probe tube passed through a felt lined bushing at the sound-source end of the impedance tube. The microphone end of the probe tube was supported by a three legged carriage with felt or rubber at the contacts between the carriage and the inside surface of the impedance tube. The felt at the microphone carriage supports and at the bushing provided vibration isolation for the microphone which is essential for accurate measurements of sound pressure. The microphones were supported by their electrical connections (thin wires) to the calibrate resistances and to the signal and calibration cables which were inside the probe tubes. A short piece of thin wall rubber tubing was placed over the calibrating resistor in the medium frequency impedance tube but, in the high frequency tube, this was removed in order to improve the vibration isolation of the microphone. The other end of the probe tube was clamped to a movable carriage which supported the microphone preamplifier.

The probe tube for the low frequency tube was 0.75 inch in diameter and about 23 feet long. The preamplifier carriage was moved along a 2 by 5 inch aluminum channel by means of an endless chain driven by a sprocket. A steel tape loop attached to the carriage was used to determine the microphone positions.

The probe tube for the medium frequency tube was 0.312 inch in diameter and 77 inches long. It was moved by means of a rack and pinion. The microphone position was indicated by a pointer on a fixed centimeter scale.

The probe for the high frequency tube was 0.25 inch in diameter and 22 inches long. It was moved by means of a lead screw and microphone position was read by reference to a fixed centimeter scale.

SAMPLE HOLDERS

A drawing of a sample holder for the low and medium frequency tubes is shown in Fig. 17. Two interchangeable sample holders, 6 ft 4 inches in length were used. The layers of acoustical materials were discs 3.5 inches in diameter and they were positioned between spacers with a 3 inch inside diameter and an outside diameter which was a slip fit in the 3-1/2 inch sample holder tube. The layer periphery was compressed slightly by the spacers. Spacers with lengths of 12, 5, 4, 3, 2 and 1 inch were made to allow a wide range of spacing patterns for the various layer systems.

In the high frequency sample holder it was not possible to compress the edge of the layers without serious deformation of the 0.76 inch-diameter area exposed to the sound. The layers were therefore fitted inside the spacers (0.76 inches I.D.) which were held in the sample holder by set screws.

In each sample holder, a hard end was provided by a movable metal plug. Felt washers clamped by metal discs, 3 inches in diameter at the front and back surfaces of the plugs were used so that the plugs could be moved inside the spacers but would be tightly sealed.

DRIVING EQUIPMENT

A block diagram of the driving and measuring equipment is shown in Fig. 18 and a list of equipment in Table V. In the driving setup the oscillator signal was applied through an attenuator to a separate power amplifier for each impedance tube. The current in each group of drivers was monitored by means of an ammeter in order to prevent excessive currents which might damage the drivers.

Low Frequency Tube

The drivers for the low frequency tube consisted of 49 8 inch cone loudspeakers, Jensen P8-PC. A photograph of the loudspeakers and the exponential horn is shown in Fig. 19. The drivers were connected in a seven by seven array and each line of seven drivers in series was fused. It was found that the resonant frequency of all the speakers was not the same and, for frequencies near 50 cps, high intensities could not be attained without damage to the cone supports. Under this condition, a few speakers which were driven near resonance had excessive amplitudes and the others, off resonance, had much smaller amplitudes. A level of 140 db, however, could be obtained even in this resonance range.

The speakers were rated at 15 watts for broadcast program material. Using a "rule of thumb" conversion factor of one-half for continuous sinusoidal signal would give a rating of 7.5 watts per speaker. For the nominal impedance of 8 ohms, the maximum current rating is 0.96 amp. For the 7 by 7 array the maximum input current is then about 7 amps and the maximum input power is 370 watts. Operation at 6 amps corresponding to 290 watts resulted in a voice coil temperature which caused discoloration of the voice coil forms, but few failures occurred except as noted for operation near resonance.

A pressure level of 160 db corresponds to an intensity of about one watt/cm^2 assuming that the impedance tube is terminated by ρc. The 3 inch diameter tube had an area of 45.6 cm^2 which gives an acoustic power requirement of about 45 watts. The efficiency of the driver and horn system (electrical input power divided by acoustic power in the impedance tube) was thus about 45/290 or 16 percent over most of the frequency range.

The speakers were mounted in a 71 by 69 inch plywood panel one inch thick and were spaced 8.5 inches on center. The panel was attached to the large end of the exponential horn which was coupled to the low frequency tube. The horn construction is described below. The space behind the speakers was a cavity of rectangular cross section, 68 by 66 by 8 inches. This space was ventilated by means of a small blower which can be seen at the upper left corner of Fig. 19. Lined ducts at the inlet and outlet openings for the cooling air were used to reduce the sound from the back of the speakers.

The cone loudspeakers were coupled to the low frequency impedance tube by an inverted exponential horn designed to provide an approximation to ρc loading for the loudspeakers. For design purposes the layer system was assumed to have high absorption and thus the impedance tube was terminated by a specific impedance of about ρc and the specific impedance looking into the source end was also approximately the same. The horn is considered as a transformer which matches the acoustical impedance of the small area at the impedance tube to the large area at the loudspeakers. The acoustical impedance is defined as the specific impedance divided by the area. Thus, a well designed horn will transform the acoustical impedance at the throat $\rho c/S_1$ to $\rho c/S_2$ at the large end and give a desirable loading for sound sources at this end.

The horn was designed on the basis of the following specifications, a 3 inch diameter at the throat, a 59 by 59 inch area at the large end for mounting 49 8 inch loudspeakers, a cut-off frequency below 50 cps, and available space and cost requirements. The equation for an exponential horn of axial length d is

$$\exp(qd) = S_2/S_1 \tag{5}$$

The flare constant q determines the cut-off frequency f_1 which is defined as

$$f_1 = qc/4\pi \tag{6}$$

For d equal to 13.6 ft and S_2/S_1 equal to $(59/3)^2$ or 388, q is o.44 ft^{-1} giving a cut-off frequency of 40 cps.

In building the horn it was decided, because of cost, to use flat plywood one inch thick for the greater part of the sides with some deviation from an exponential expansion in area. The length was divided into seven segments. The first was 19 inches long and was made of 1/4 inch sheet steel which was formed to have a circular cross section 3 inches in diameter at the impedance tube end and a square cross section at the other end. The

following segments were made of plywood and were each two feet long. They were hollow pyramids with a square cross section. At each junction between segments, the width of the segment was fitted to the exponential curve specified in the preceding paragraph. The large end of the horn was closed by a 59 by 59 inch flat plywood panel on which the 49 loudspeakers were mounted in a seven by seven array approximately 8.5 inches on center.

The axis of the horn was inclined from the impedance tube axis as shown in Fig. 15. The angle between the axes was about 14°. A flanged steel tube, 3 inch I.D. and about 3 ft long was bent to connect the impedance tube and horn so that there was no interference between the microphone probe tube and its preamplifier carriage and the horn.

Although the stepped horn differed from a theoretical exponential horn in several respects and there was an abrupt change from the 59 by 59 inch area of the horn to the smaller area of the 49 loudspeakers cones, the horn did not introduce pronounced peaks and dips in the frequency response of the system. The loading of the loudspeaker drivers was adequate to give a fairly high efficiency for the conversion of electrical power to acoustic power in the impedance tube.

All joints between the plywood sides of the horn were closely fitted and were glued and screwed together. The various segments were mounted in an enclosure filled with sand as described previously. A photograph of the loudspeaker array and horn assembly is shown in Fig. 19.

Medium Frequency Tube

The drivers for the medium frequency tube consisted of 16 University Horn Drivers, Model ID-60. The nominal impedance was 16 ohms and the rated power per driver was 60 watts. Dividing the power rating by two to convert to an approximate rating for continuous sinusoidal signals gives 30 watts and a maximum current of 1.37 amps. The drivers were connected in a 4 by 4 array with each line of four speakers fused at 1 amp. With a maximum current of 4 amps for the array corresponding to a maximum input power of 250 watts, the required sound level could be attained. A photograph of the horn drivers is shown in Fig. 20.

The acoustic power corresponding to 160 db pressure level with a ρc termination of the impedance tube is 45 watts the same as calculated for the low frequency tube. The efficiency of the driving system is thus about 45/250 or 18 percent.

The 16 horn drivers were coupled to the impedance tube by a series of Y connectors of circular cross section which provided a fairly smooth area transformation from the driver throat (approximately 7/8 inch diameter) to the impedance tube (3 inch diameter). The path length from each driver to the impedance tube was the same within 1/32 inch to keep their sound outputs in phase.

High Frequency Tube

Two Jensen high frequency horn drivers, Model RP 103, were used as the sound source for the high frequency tube. They were mounted on the impedance tube by a Y-coupling. A photograph of the high frequency impedance tube is shown in Fig. 16. The nominal impedance was 16 ohms and the drivers were connected in series. A maximum current rating of 0.5 amp was determined from a curve of voice coil resistance versus current. This value gives an input power of 8 watts and was adequate for producing the required sound intensity of 160 db.

The area of the high frequency tube was 2.93 cm^2 and the acoustic power for 160 db sound pressure level with a ρc termination was 2.9 watts. The efficiency of the driving system is thus about 2.9/8 or 36 percent.

MEASURING EQUIPMENT FOR IMPEDANCE TUBES

A block diagram of the measuring system is shown in Fig. 18. A list of the equipment is given in Table VI. In general it is a conventional system for this type of work consisting of a microphone, amplifiers, attenuator, filter and vacuum tube voltmeter. Since the sound pressures are high and must be measured in absolute levels, high intensity microphones must be used and they must be located at the measuring point inside the impedance tube. In the usual installation where only relative pressure levels are required, a probe tube is used to conduct the sound from the measuring point inside the tube to the microphone outside. Measurement of absolute sound pressure level with such a probe microphone would then require calibration of the resonant probe tube and microphone system at each frequency. When a calibrated microphone is located inside the impedance tube, the only requirements are a small diameter and adequate vibration isolation for the microphone. The small size minimizes changes in the sound field due to the presence of the microphone and vibration isolation prevents transmission of vibration from the impedance tube wall to the microphone.

For the medium and high frequency impedance tubes, a Massa, M-213 microphone was used. This is a compression type crystal microphone which is 0.25 inches in diameter and 0.5 inches in length. Its sensitivity is -102 db re 1 V per dyne/cm^2. Although it has a low capacitance, 12 $\mu\mu f$, a moderate length of cable between the microphone and its preamplifier can be used (about 77 inches for the medium frequency tube and 22 inches for the high frequency tube) without excessive reduction of sensitivity or increase in noise threshold. The insert calibration resistor must, however, be located close to the microphone for a correct calibration by means of the conventional insert voltage calibration technique.

The probe tube for the low frequency is 23 feet long and this length of signal cable has too much capacitance for the M-213 microphone. A Massa M-101 microphone was therefore used in this installation. It is 5/8 inches in diameter and one inch long and has a capacitance of about 125 $\mu\mu f$ and a sensitivity of -93.5 db re 1 V per dyne/cm^2.

In order to prevent overload of the preamplifier for the M-101 microphone, a small capacitance was connected across the input circuit to reduce the signal level by about 20 db. This capacitance voltage divider had a negligible effect on the frequency characteristic of the microphone. It is, of course, part of the system which is calibrated by the insert voltage calibration technique.

The electrical part of the measuring system was checked routinely by observing the output voltage and waveform produced by a calibrating signal at the insert resistor in series with the microphone. The calibrate voltage was made equal to the microphone voltage from the desired acoustical signal both in frequency and magnitude. Observation of the output voltage waveform on an oscilloscope was made routinely during impedance tube measurements to check the filter settings and to guard against overload. In the initial testing of the measuring system, it was found that there was a non-linear relation between filter input and output voltages when the latter exceeded about 4 mv. Care was taken not to exceed this limit during all tests.

FLOW MEASURING FACILITY

A photograph of the flow measuring apparatus is shown in Fig. 21. Air was drawn through the sample placed in the vertical cylinder at the right end of the table by means of centrifugal type blowers. The volume velocity was measured by means of one of the six flow meters mounted in the back panel. The pressure drop across the sample was measured by the inclined manometer, 0 - 2 cm of water, or by the vertical manometer, 0 - 20 inches of water. An existing measuring system was modified for this application. The previous use required the cylindrical and rectangular sample holders seen at the left of Fig. 21. Each flow meter was supplied with regulating and shut-off valves and the manometers could be connected to any one of the sample holders by means of valves. A list of the flow meter type numbers and ranges is given in Table VII.

Test samples were fitted to the 3.5 inch I.D. sample holder and were supported by a 0.75 inch mesh wire grid which had negligible flow resistance. The manometers were connected to a cavity below the sample, 3.5 inches in diameter and 2 inches in length. The sample holder and the largest flow meter were connected to the blower with 1.5 inch piping to reduce flow loss in the system.

Thick samples were made to fit tightly in the sample holder. Thin samples such as wire screen or glass cloth were sealed by clamping at the circumference by means of a 3.06 inch I.D. tube which fitted inside the 3.5 inch I.D. sample holder. The linear flow velocity corresponding to the maximum flow rate of 37,500 cm^3/sec was 600 cm/sec for the area of the 3.06 inch tube and 790 cm/sec for the area of the 3.5 inch tube. These values are well above the required RMS particle velocity of 480 cm/sec corresponding to a plane wave at a sound pressure level of 160 db.

APPENDIX II

THEORY AND CALCULATION OF LAYER SYSTEM ABSORPTION

In this appendix, a theory for calculation of the normal incidence absorption is given and the results of approximate calculations of absorption of particular layer systems at low frequencies.

THEORY FOR CALCULATION OF IMPEDANCE OF MULTIPLE LAYERS

The relation between the normalized specific impedance Z at a surface and the absorption α_N of an acoustic wave at normal incidence is given in various acoustic textbooks (Ref. 6, 7, 8, 9). It can be expressed as

$$\frac{\alpha_N}{100} = 1 - \left(\frac{1 - Z}{1 + Z}\right)^2 \tag{7}$$

Since $Z = R + jX$

$$\frac{\alpha_N}{100} = \frac{4R}{(1 + R)^2 + X^2} \tag{8}$$

In these relations and throughout the report, the impedance Z is the normalized impedance, the ratio of sound pressure to particle velocity normal to the surface divided by ρc for air.

Equation (8) represents a family of circles with constant values of α_N on the R, X plane with centers at

$$X = 0$$

$$\text{and} \qquad R = \frac{200}{\alpha_N} - 1 \tag{9}$$

and with radii equal to

$$\left[\left(1 - \frac{200}{a_N}\right)^2 - 1\right]^{1/2} \qquad (10)$$

A family of circles for a_N between 70 and 100 percent are shown in Fig. 22. The design goal of 96 percent absorption requires impedance values inside the 96 percent circle. It is seen that values of X should be small with a maximum range of $\pm$ 0.416 when R is 1.08. For X equal to zero, R must lie between 0.667 and 1.50.

The impedance of material systems is a function of frequency and at high sound intensities it is also a function of other variables such as particle velocity (see Figs. 1 and 3).

For homogeneous materials backed by a reflective surface the impedance, at least at low intensity, can be approximately related to measured properties of the material (Ref. 7, 8). In systems, such as a number of spaced layers of absorbing materials, the impedance at the surface of sound incidence is a more complicated function involving layer spacing.

The calculation of the impedance of a layer system at normal incidence is most easily done by a series of steps. Following Zwikker (Ref. 7 Chapter 6, Article 7) who gives a graph'cal method, the impedance at the surface of a layer of material can be determined from the characteristic impedance and propagation constant of the layer material and the backing impedance. Referring to the diagram of a layer system in Fig. 23, the upper part shows a layer system with spacings d and layer thicknesses ℓ The process of calculation proceeds in steps which are based on the equation (Ref. 7 Chapter 1, Article 2) for the specific impedance z_{11} of layer 1 which is backed by the specific impedance z_{10}

$$Z_{11} = w_1 \frac{z_{10} \cosh(\Gamma_1 \ell_1) + w_1 \sinh(\Gamma_1 \ell_1)}{z_{10} \sinh(\Gamma_1 \ell_1) + w_1 \cosh(\Gamma_1 \ell_1)}, \qquad (11)$$

where w_1 is the characteristic impedance of the material of layer 1 and Γ_1 is its propagation constant. Both of these quantities are complex. It is interesting to note that for a hard end backing where z_{10} is infinity

$$z_{11} = w_1 \coth \Gamma_1 \ell_1 \quad , \qquad (12)$$

and for zero impedance backing

$$z_{11} = w_1 \tanh \Gamma_1 \ell_1 \quad , \tag{13}$$

thus giving a method of determining w_1 and Γ_1 from impedance measurements. The calculation of layer system impedance can be done by successive applications of Eq (11), starting from the infinite impedance of the hard end and calculating z_{10}, z_{11}, z_{20} etc. The calculation is complicated and tedious and Zwikker (Ref. 7, Chapter 1) describes a graphical method.

A Smith Chart Calculation (Ref. 10) can be used to facilitate these calculations since it provides a rapid means of evaluating the real and imaginary parts of the hyperbolic cotangent of a complex quantity. The Smith Chart, however, uses normalized quantities and specific impedances must be renormalized in passing through the boundaries of each layer.

The steps according to Zwikker (Ref. 7, Chapter 6, Article 7) are shown below. In the air at the left surface of layer 1 (Fig. 23)

$$Z_{10} = \coth(-jd_1/\lambda) = j \cot(d_1\lambda) \tag{14}$$

and

$$z_{10} = j\rho c \cot(d_1/\lambda) \tag{15}$$

In the material just inside this surface, the specific impedance is the same but, to use the Smith Chart to calculate z_{11}, z_{10} must be normalized by dividing by w_1 to get Z'_{10},

$$Z'_{10} = z_{10}/w_1 \tag{16}$$

The impedance Z'_{11}, still normalized to the material in layer 1 is obtained from the Smith Chart by evaluating Z'_{11} from

$$Z'_{11} = \coth(\Gamma_1 \ell_1 + \coth^{-1} Z'_{10}) \tag{17}$$

which is the impedance in the material at its right hand surface. Renormalizing to obtain Z_{11} for the impedance in the air at this surface requires the use of

$$Z_{11} = Z'_{11} w_1/\rho c \tag{18}$$

This process is repeated until the impedance is obtained at the incident sound boundary of the whole system which is converted to normal incidence absorption by the use of Eq (8).

Even with the use of the Smith Chart this calculation is tedious and is not particularly accurate because of uncertainties in w and Γ for the layer material. Beranek (Ref. 8) and Zwikker (Ref. 7) give methods of calculating these quantities from measurable properties of absorbing materials and Beranek (Ref. 8, Chapter 12) gives curves for conventional absorbing materials. For the materials such as polyurethane foam or wire screens which are adapted to layer systems for high intensity sound, the material properties are not available. It was therefore decided to use an approximate calculation method described below.

THEORY FOR APPROXIMATE CALCULATION OF LAYER SYSTEM ABSORPTION

If certain assumptions are made regarding attenuation and phase shift in passing through a layer of material, the combination of transmission line segments and lumped resistances of the central part of Fig. 23 can be used. This greatly simplifies the calculation of the absorption of a layer system. If the portion of the transmission line in the layer material can be replaced by the resistance r, it must be shown that r is approximately equal to the impedance z of the layer with zero impedance backing. The characteristic impedance is related to the propagation constant (Ref. 8, Eq 12.14) by

$$w = \frac{-jK\Gamma}{\omega Y} \tag{19}$$

The porosity Y for the porous materials in question can be taken as approximately unity. Since the velocity of sound in the material is $(K/\rho)^{1/2}$, Eq (19) can be given as

$$w = \frac{-j\rho c^2 \Gamma}{\omega} \tag{20}$$

and

$$z = \frac{-j\rho c^2 \Gamma}{\omega} \tanh(\Gamma \ell) \tag{21}$$

The propagation constant Γ is composed of a real part θ the attenuation in nepers per unit length and an imaginary part β, the phase shift per unit length equal to ω/c. For thin layers $\Gamma \ell$ is very small and $\tanh(\Gamma \ell)$ can be replaced by its argument without serious error in Eq (21) to give

$$z \simeq \frac{-j\rho c^2 \Gamma^2 \ell}{\omega} \tag{22}$$

Replacing Γ^2 by

$$\begin{aligned} \Gamma^2 &= (\theta + j\,\omega/c)^2 \\ &= \theta^2 - \omega^2/c^2 + 2j\theta\omega/c \end{aligned}$$

gives

$$z \simeq \rho c \ell \left[2\theta - j(c\theta^2/\omega - \omega/c)\right] \tag{23}$$

This impedance normalized with respect to ρc for air is the impedance which was measured (Section IV) for a layer backed by a quarter wave length stub. Since this measured impedance was essentially resistive, the imaginary part of Eq (23) can be neglected to give

$$z \simeq 2\rho c\theta \ell \tag{24}$$

and the impedance of a layer with zero impedance backing is approximately equal to a resistance which is proportional to the thickness.

CALCULATED ABSORPTIONS OF LAYER SYSTEMS

Impedance calculations were made for six layer systems having constant resistance R_{AC} per layer and the spacings of system No. 1 in order to determine how the normal incidence absorption varied with layer resistance. These calculations, made before the measuring system was completed, were intended to show:

1) Whether absorption coefficients in the neighborhood of 96 percent could be obtained with systems with a small number of layers.

2) The size of irregularities to be expected in the absorption versus frequency curve for systems with as few as six layers.

3) The effect on the absorption of changes in sound intensity which were known to affect resistance.

The calculations were based on the equivalent transmission line diagram of Fig. 23 using the equations given below this diagram. Hyperbolic cotangents were evaluated by means of the Smith Chart (Ref. 10) to obtain Z_{10}, Z_{11}, Z_{20}, Z_{21} ----- Z_{61} and the normal incidence coefficient of the system was obtained by the use of Eq (9).

The calculated values of α_N are listed in Table VIII for a range of layer resistance at various frequencies. Two of the frequencies, 94.4 and 472 cps, were chosen in order to investigate dips in the absorption versus frequency curve which might occur when the length of the whole system was equal to a whole number of half wave lengths. The remaining frequencies covered the low frequency range between 50 and 500 cps.

It is seen from Table VIII that calculated absorption coefficients were lower at $R_{AC} = 0.1$ and increased to a broad maximum at about $R_{AC} = 0.4$. The first experimental test (System No. 1) was therefore made with layer resistances close to this value. The variations in calculated absorption at different frequencies was larger than the variations found in the experimental tests but the differences between calculated and experimental values were not extreme.

The calculations of absorption were justified as a preliminary evaluation of a layer-type treatment in showing that high absorption could be obtained with a system of six layers and that changes in absorption of such a system were not excessive for a moderate range of layer resistance.

EFFECT OF SURFACE DENSITY OF LAYERS

In the previous discussion it was assumed that the resistance of a layer was not greatly affected by layer motion caused by the sound. This motion can be considered as a wave motion in the layer material in addition to a simple translation motion where all parts of the layer move in phase. Wave motion in a layer causing expansion and contraction in the layer material is small for layer thicknesses which are short compared to a wave length. Its effect on layer impedance did not introduce a significant reactive term as evidenced by measurements of R_{AC} at frequencies below 1500 cps. The effect on the resistive term is also probably small and is taken care of by using an experimentally determined lumped resistance.

Translation motion of the whole layer, however, has a significant effect on layer impedance at low frequencies especially for materials of low surface density. The effect of the motion for normal incidence sound on a layer of large area depends on the impedance of a stationary layer (assumed to be a resistance), the surface density of the layer, the frequency, and the backing impedance for the layer. It was decided to calculate the specific impedance of a layer backed by an impedance of ρc to determine the surface density at which layer motion would have negligible effect on layer impedance. This case of ρc impedance backing was chosen because of convenience and because it is fairly representative of conditions at low frequencies near the incident sound end of an absorbing layer system.

For an impervious layer with a surface density m, the velocity of motion is equal to the force divided by the mass reactance, $-j\omega m$. The force is the difference in pressure between the two surfaces. For ρc backing the particle velocity in the air just beyond the surface can be shown to be equal to the velocity of the material. For a pervious stationary layer of impedance r the particle velocity in the backing space is the same difference in pressure divided by r. For conditions of both motion and flow, the system is analogous to an electrical resistance r in parallel with an inductance ωm with this parallel combination in series with a resistance ρc. This analogy was used by Beranek (Ref. 8, Chapter 14) to calculate the transmission loss through a porous layer. The input impedance z of this circuit can be determined by elementary electrical circuit theory to be

$$z = \frac{-jr\omega m}{r - j\omega m} + \rho c \tag{25}$$

Dividing by ρc to transform to normalized impedances, denoted by capital letters, rationalizing the denominator, and simplifying gives

$$Z = \frac{R + 1 + R^2/\omega^2 M^2 - jR^2/\omega M}{1 + R^2/\omega^2 M^2} \tag{26}$$

When $R/\omega M \ll 1$ (at high frequency for a given R/M), the impedance is approximately equal to $R + 1$ which is correct for a stationary layer with backing. For low frequencies where $R/\omega M$ is not small, the effect of motion is a reduction of the resistive term for a stationary layer and the addition of a negative reactive term.

Using Eq (26), calculations were made of lumped impedance for the layers of system No. 10 for surface densities between 0.1 and 0.5 lbs/ft^2. These values were then used to calculate absorption coefficients for this system at various frequencies giving the results shown in Table II. As explained in Section III, the calculated absorption values could not be checked against values measured in an acoustic tube because the boundary conditions of the 3 inch diameter layers in the impedance tubes was quite different from the boundary conditions of layers of infinite extent used in the calculations. The calculated values were used in determining surface density of screens to support the layers in the recommended treatment.

APPENDIX III

CALCULATION OF REVERBERANT ROOM CONDITIONS

There has been a question about the desirability of removing the ceiling treatment when the ASD room is to be used for tests requiring a reverberant field. If the ceiling treatment is collapsed and remains in the room it will have considerable absorption which may be undesirable in obtaining optimum reverberant conditions. The wall treatment cannot be conveniently removed from the room and even when collapsed will provide much more absorption than the untreated room surfaces. Calculation and estimation of conditions for a reverberant or diffuse sound field in the ASD room are given below.

In a diffuse sound field, energy flows toward a surface equally from all directions and the sound pressure level is constant at all points in the field. In a room designed for such a field, the reverberation time should be long and the minimum distance from a sound source at which diffuse field conditions exist should be short.

In order to make a rough estimate of the reverberation times of the room with ceiling treatment collapsed and with ceiling treatment removed, the conventional reverberation formula will be used, i.e.,

$$T = 0.049\, V/A \tag{27}$$

The total amount of absorption, A, was obtained from calculation or estimation of the absorption of the various room surfaces and is shown in Table IX. In these calculations, random coefficients α_R are used. Absorption coefficients for the collapsed ceiling treatment were estimated from the normal incidence coefficients measured in the impedance tube for system No. 25 which had the same layers as the recommended system No. 11 but had been collapsed. The absorption curve for this collapsed system is given in Fig. 4(y) and its description in Table III (f). A spacing of 30 inches between the hard end (ceiling) and layer No. 1 was used and a one inch space between layers was assumed to account for the supporting frames. Above 600 cps the absorption coefficients for the collapsed treatment are above 96 percent but below this frequency the curve is irregular and considerably below the curve for the extended treatment shown in Fig. 4(m). Measurements were also made on the system collapsed to within four inches from the ceiling. The results (not shown) were similar to Fig. 4(y) except for lower coefficients below 125 cps.

In the approximate calculations for Table IX, normal incidence coefficients were used for the treated surfaces although these are not generally equal to random incidence coefficients. An average coefficient of 90 percent was used for the collapsed ceiling treatment, although Fig. 5 shows about 96 percent above 600 cps and about 85 percent below this frequency. The same coefficient of 90 percent was assumed for the collapsed wall treatment and the total absorption was based on panels 10 feet high which would have horizontal surfaces 6 feet wide and vertical surfaces 10 feet wide with ceiling treatment removed and 6.5 feet wide with collapsed ceiling treatment in place.

The reverberation times with collapsed treatment given in Table X are rather short and the direct field from a sound source will, therefore, extend for a considerable distance from the source. Hopkins and Stryker (Ref. 11) and also Beranek (Ref. 9, p. 317) give curves of sound pressure versus distance from a non-directional sound source for a range of values of the room constant B which is defined as

$$B = \frac{A}{1 - \alpha_a} \qquad (28)$$

where α_a is the average absorption coefficient of the room surface

Table XI gives values of R and the approximate amounts that the total sound level from a non-directional sound source is above the level of the direct sound from the source at distances of 10 and 20 ft. These level differences were obtained by interpolation from the curves of Ref. 11 which is a sufficiently accurate method considering the rough estimates of random absorption coefficients for the treatment.

A good approximation of an anechoic field exists for the extended treatment. For the collapsed treatment the total field is only 3 db above the direct sound at 10 feet but semi-reverberant field conditions exist at 20 ft. For the collapsed treatment with ceiling treatment removed, a considerably better approximation to reverberant field conditions exists at 20 ft. With no treatment, a reverberant field exists at distances less than 10 ft.

Removal of the ceiling treatment will therefore be beneficial in exposing structures to reverberant sound fields. If this approximation of a reverberant sound field for the collapsed treatment is not acceptable, the possibility of removing both the ceiling and wall treatments can be considered. This should not be necessary provided that test structures can be located about 20 ft from the sound sources.

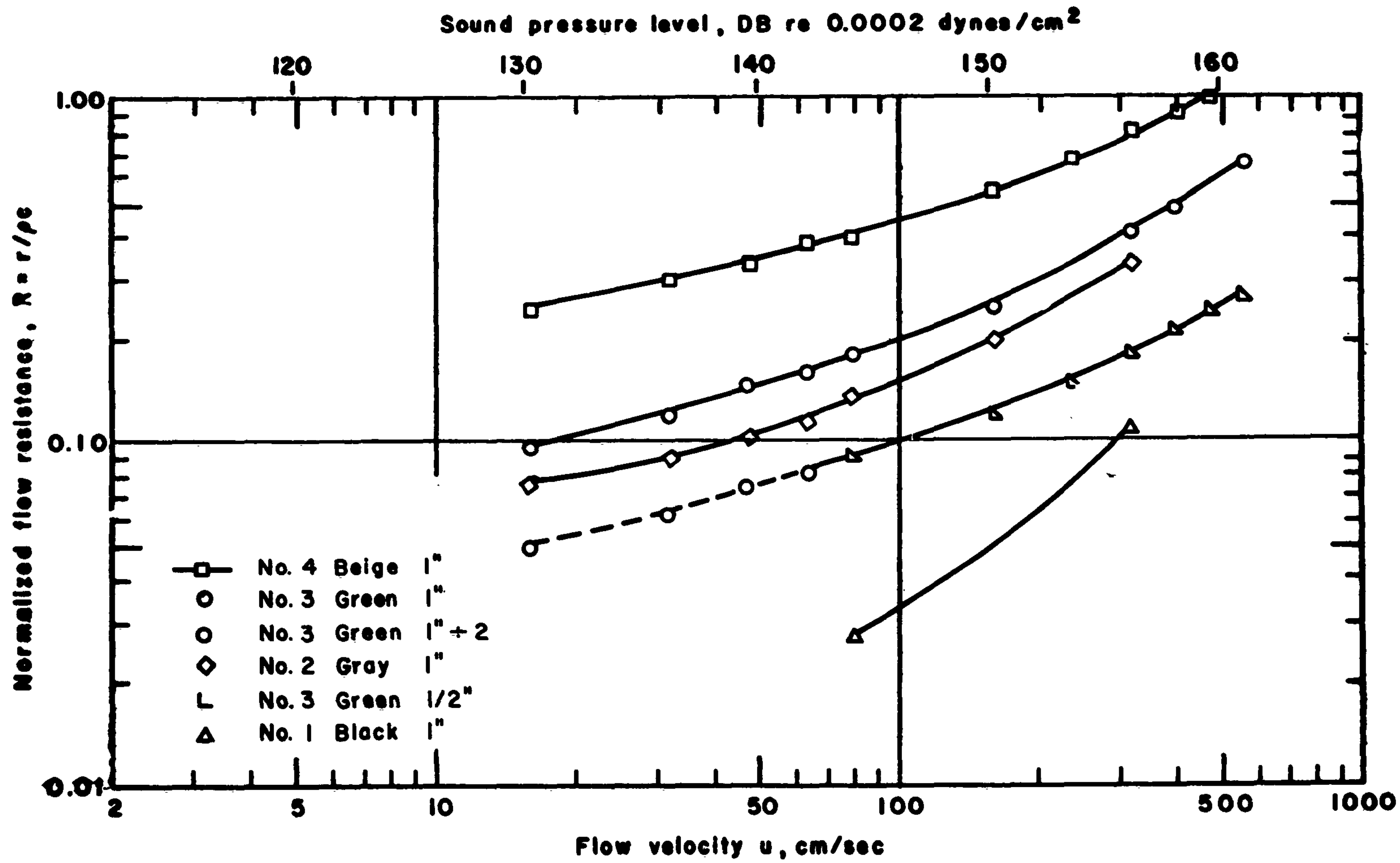


Figure 1. DC Flow Resistance of Materials
(a) Polyurethane Foam Etched Nos. 1, 2, 3, 4, See Table I (a)

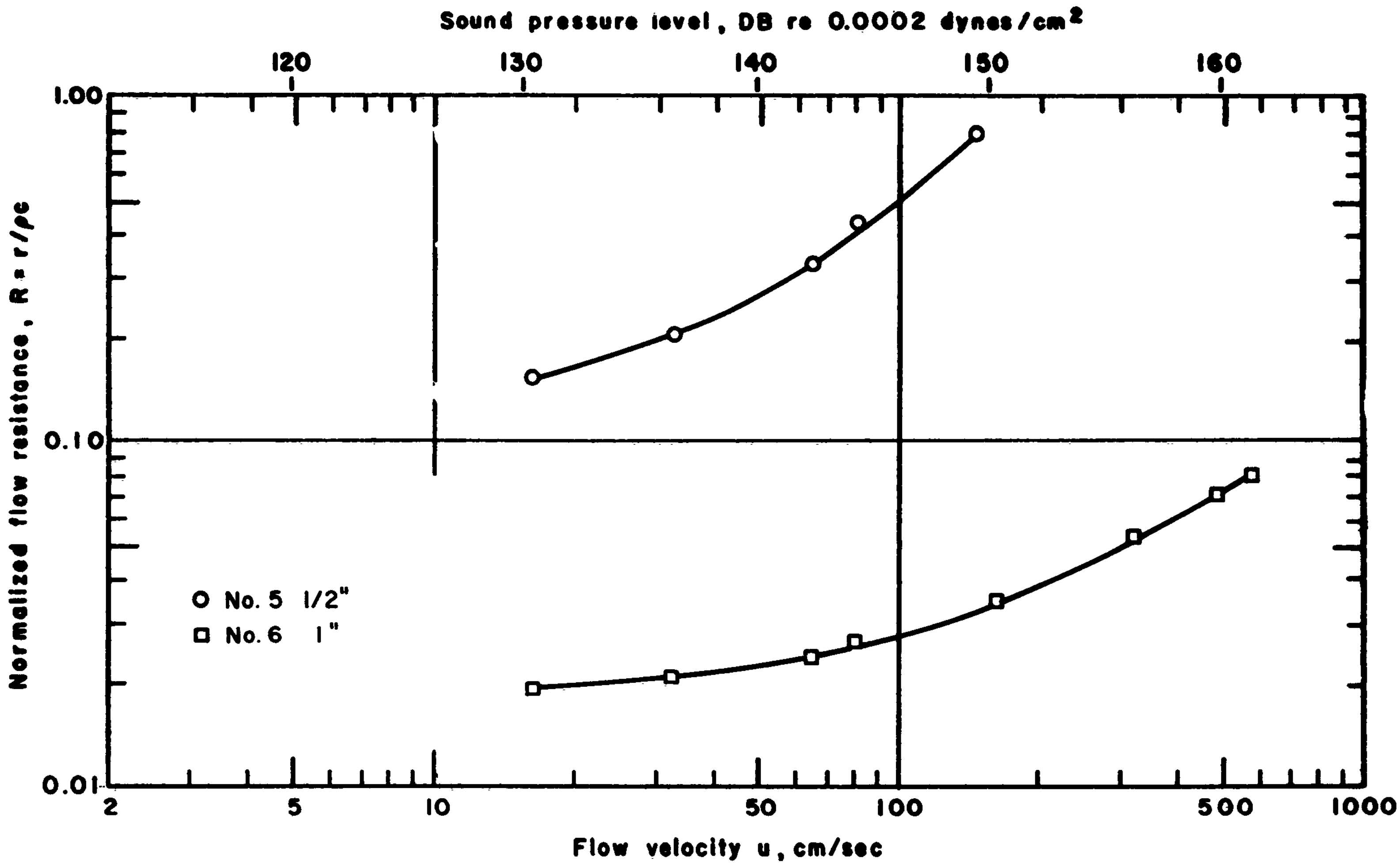


Figure 1. DC Flow Resistance of Materials
(b) Polyurethane Foam Nos. 5, 6, See Table I (a)

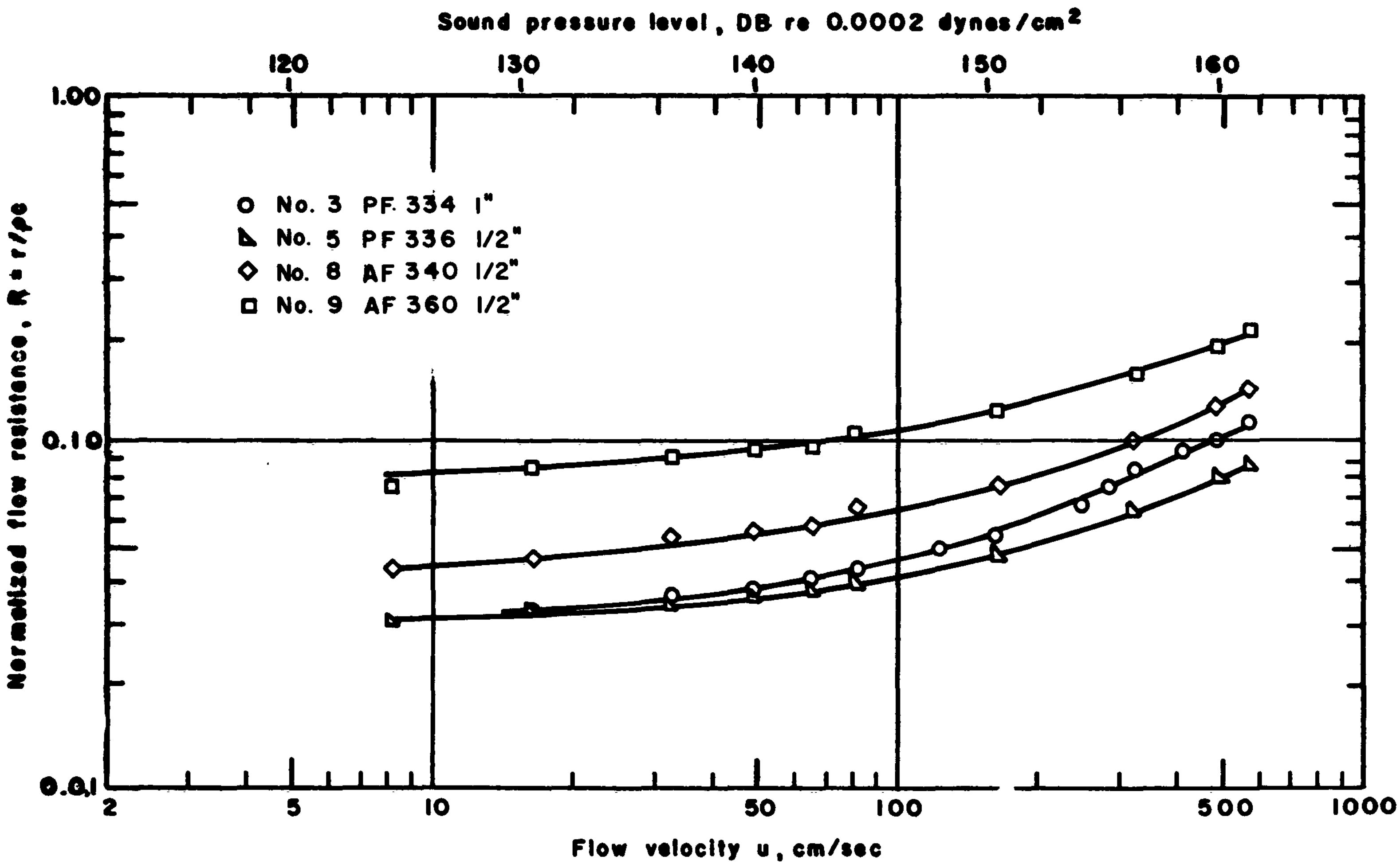


Figure 1. DC Flow Resistance of Materials
(c) Fiberglas Nos. 3, 5, 8, 9, See Table I (b)

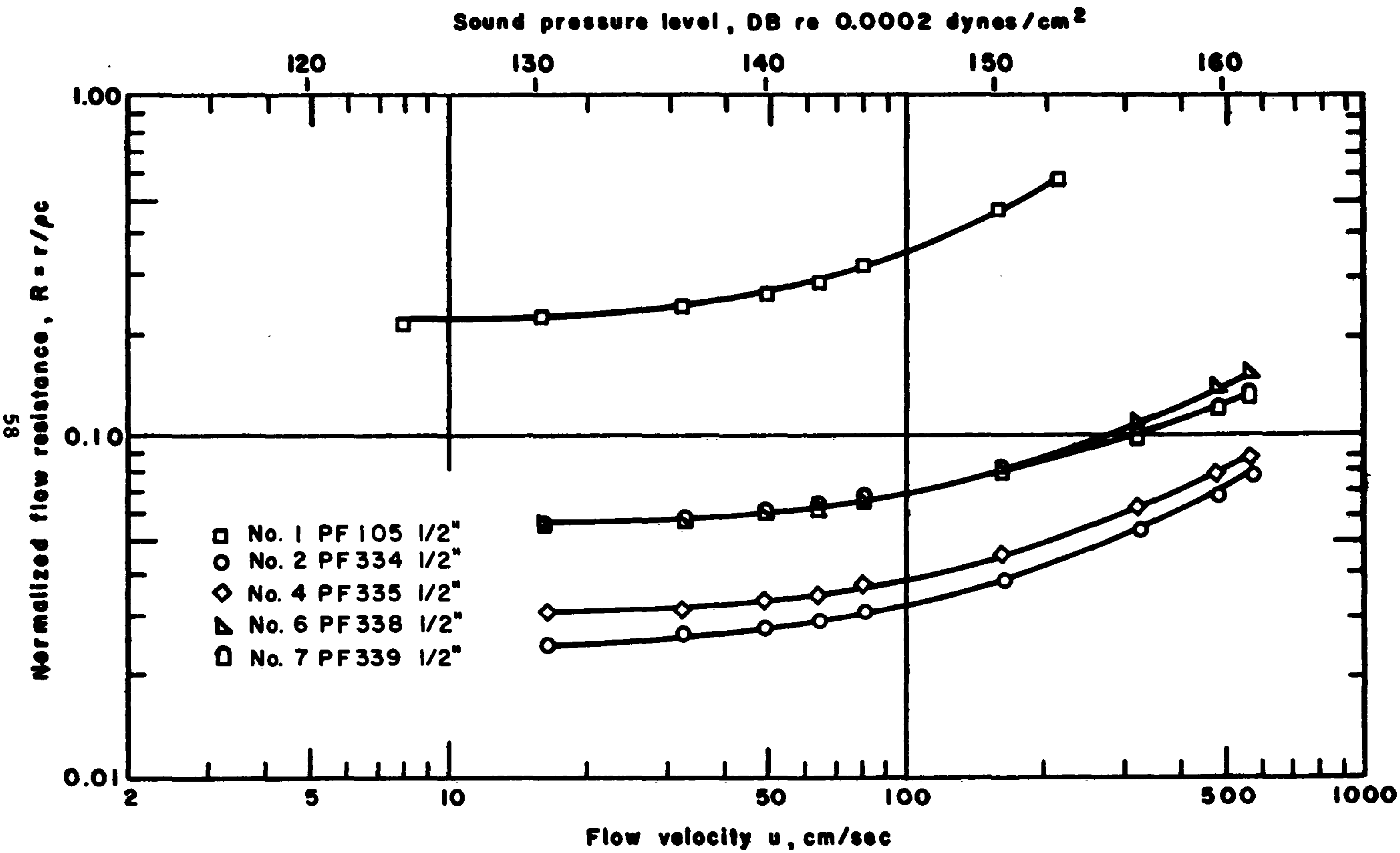


Figure 1. DC Flow Resistance of Materials
(d) Fiberglas Nos. 1, 2, 4, 6, 7, See Table I (b)

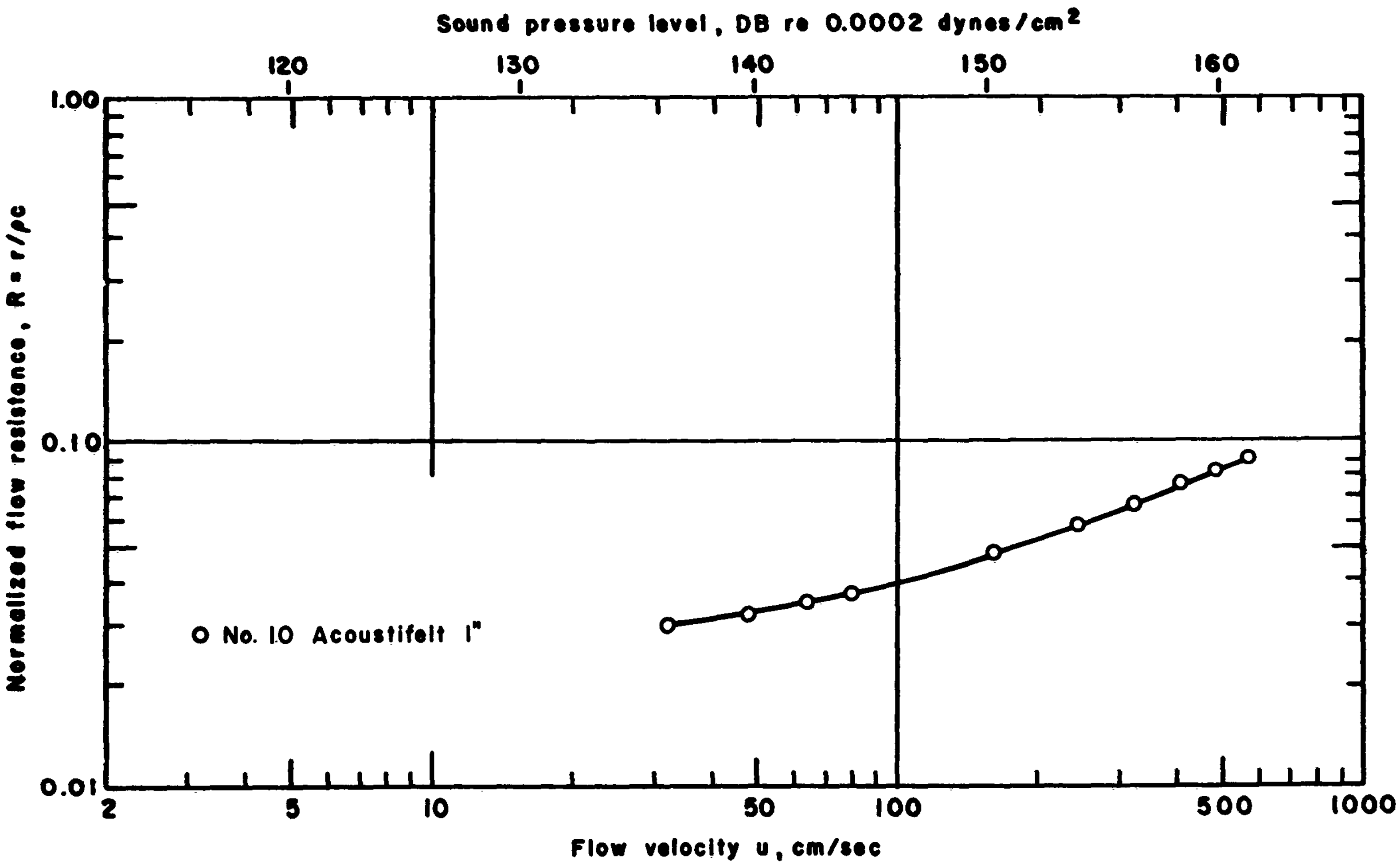


Figure 1. DC Flow Resistance of Materials
(e) Glass Wool No. 10 See Table I (b)

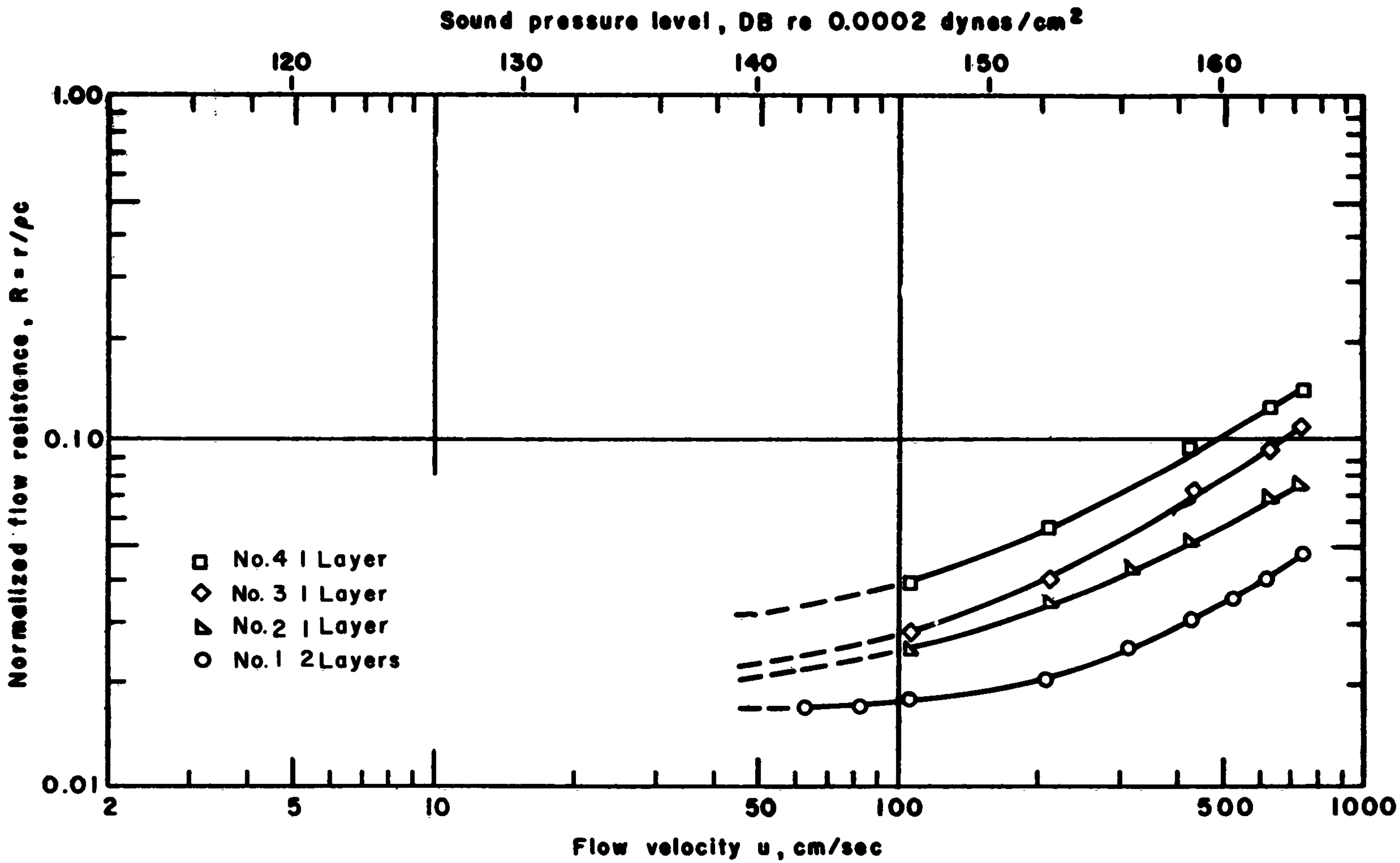


Figure 1. DC Flow Resistance of Materials
(f) Wire Screens Nos. 1, 2, 3, 4, See Table I (c)

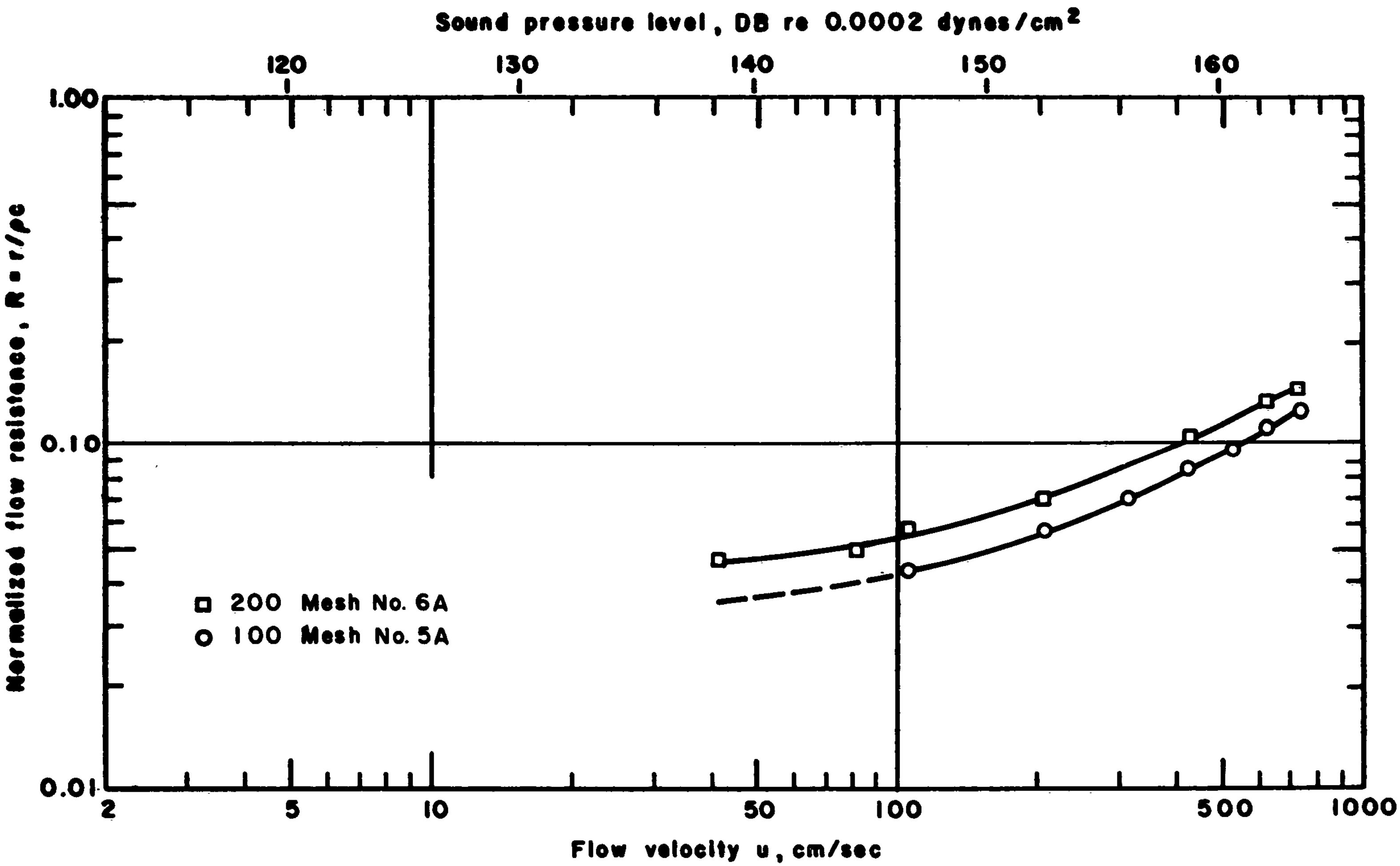


Figure 1. DC Flow Resistance of Materials
(g) Wire Screens Nos. 5A, 6A Sandwiched between 20 Mesh Screens See Table I (c)

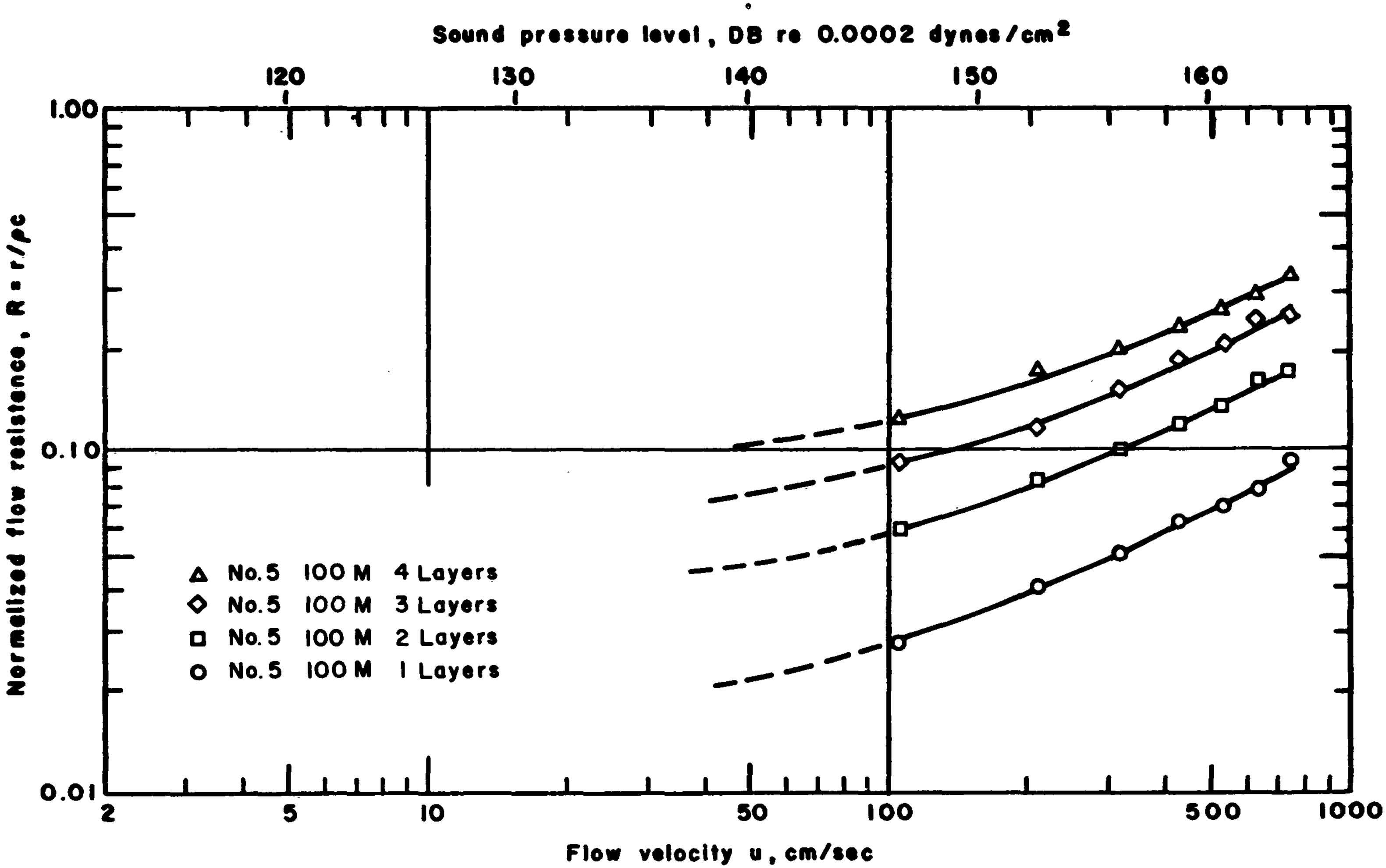


Figure 1. DC Flow Resistance of Materials
(h) Wire Screen No. 5, 1 - 4 Layers See Table I (c)

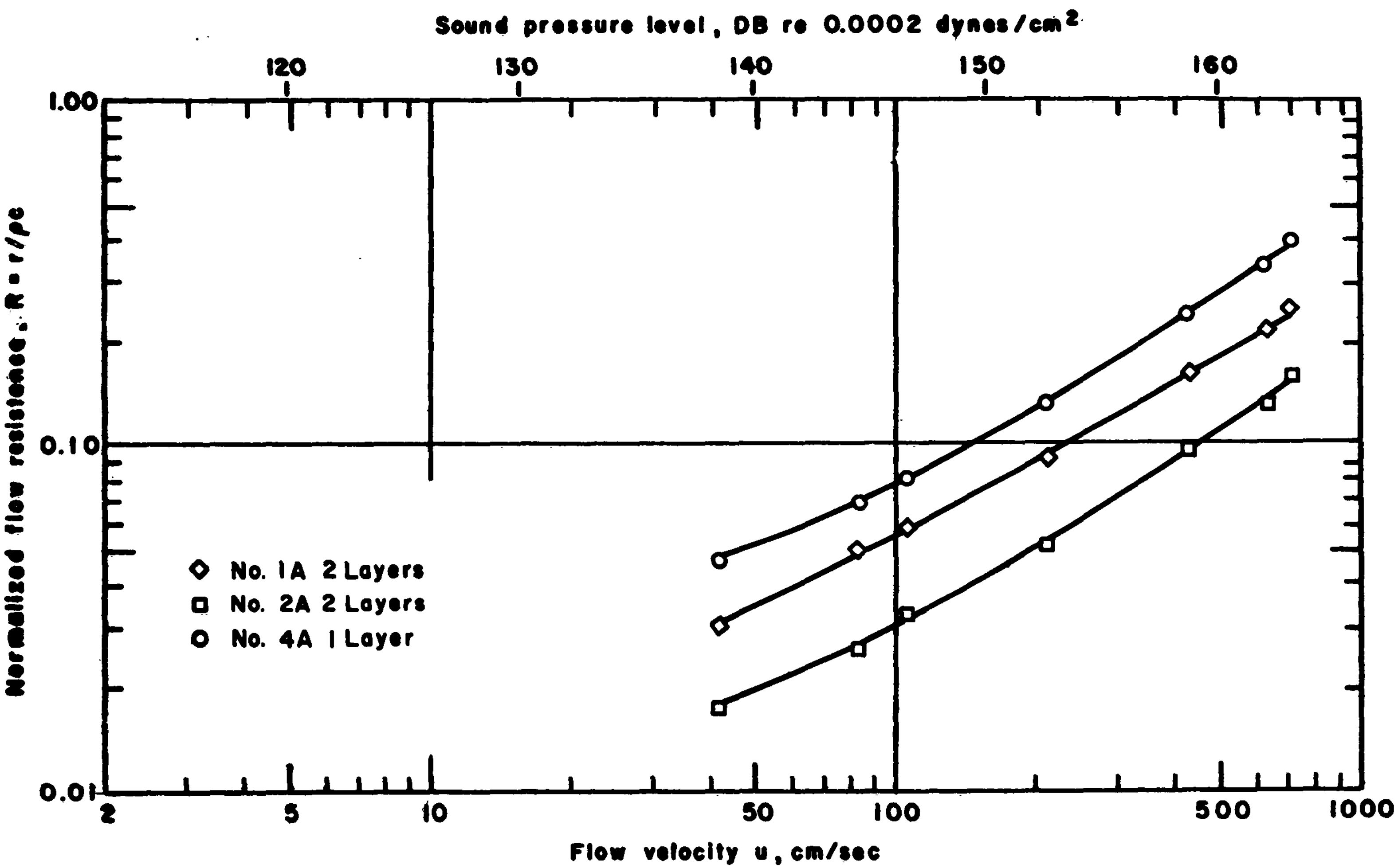


Figure 1. DC Flow Resistance of Materials
(i) Glass Fiber Cloth Nos. 1A, 2A, 4A, See Table I (d)

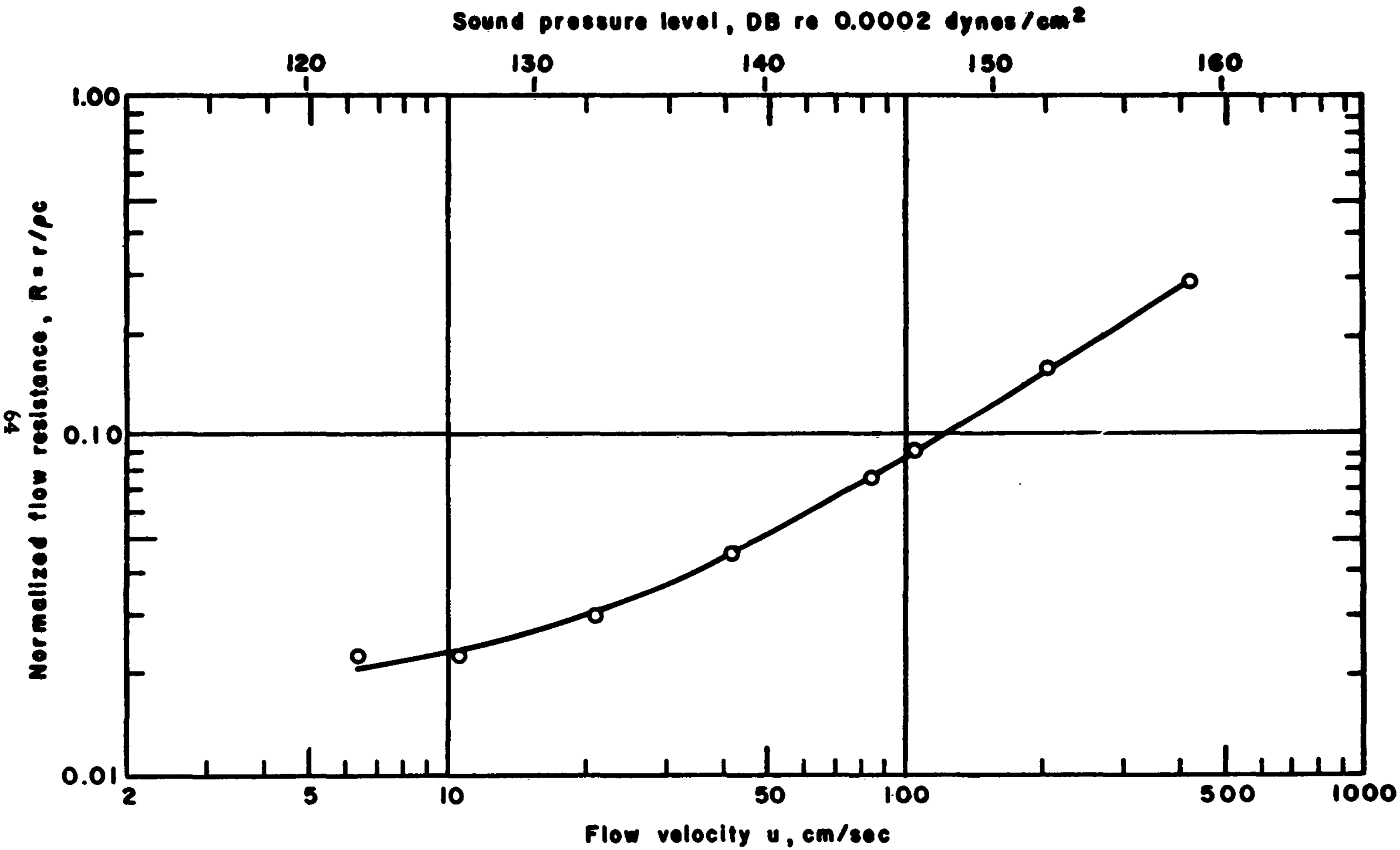


Figure 1. DC Flow Resistance of Materials
(j) Glass Fiber Cloth No. 3A, 1 Layer See Table I (d)

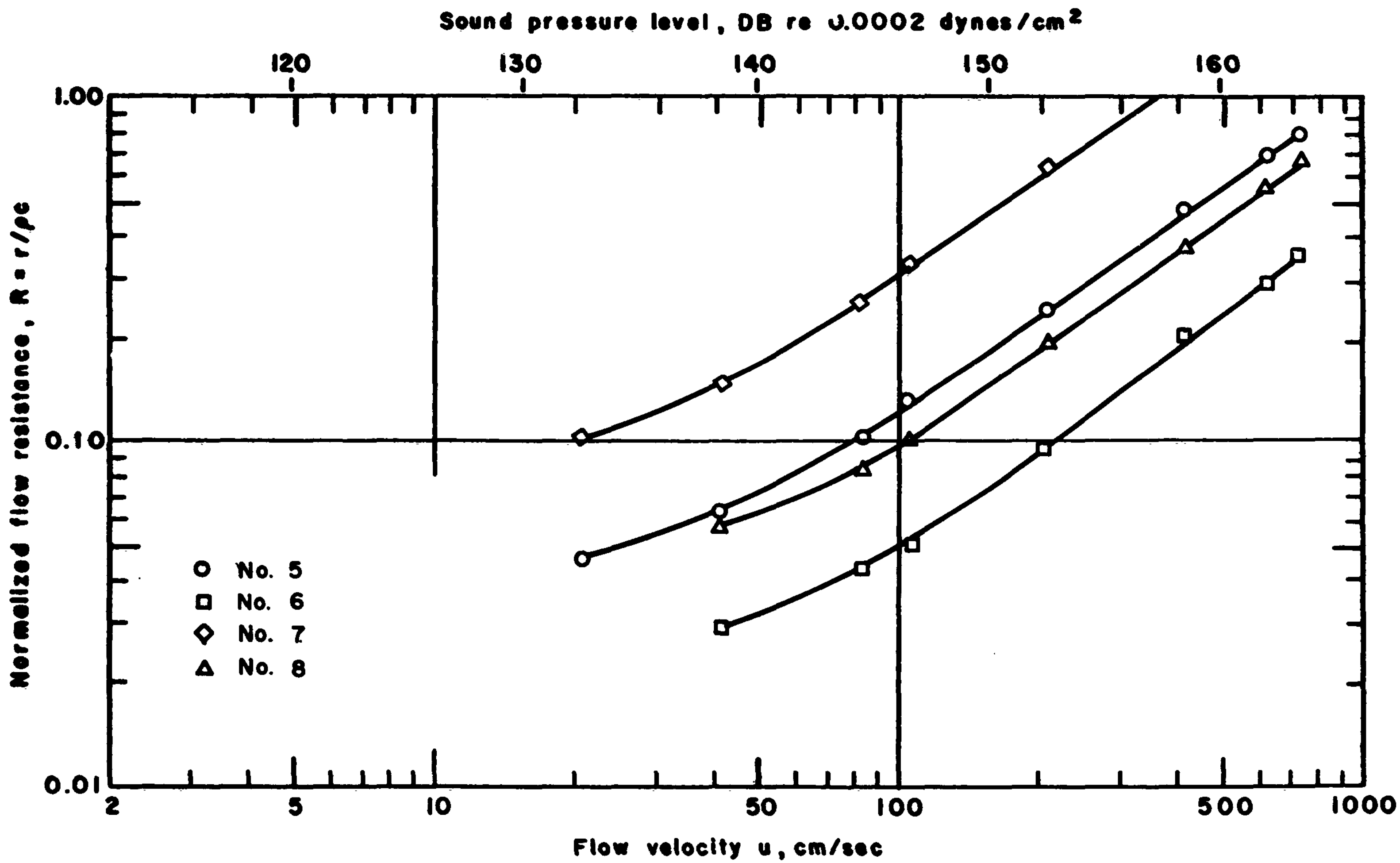


Figure 1. DC Flow Resistance of Materials
(k) Glass Fiber Cloth Nos. 5, 6, 7, 8, See Table I (d)

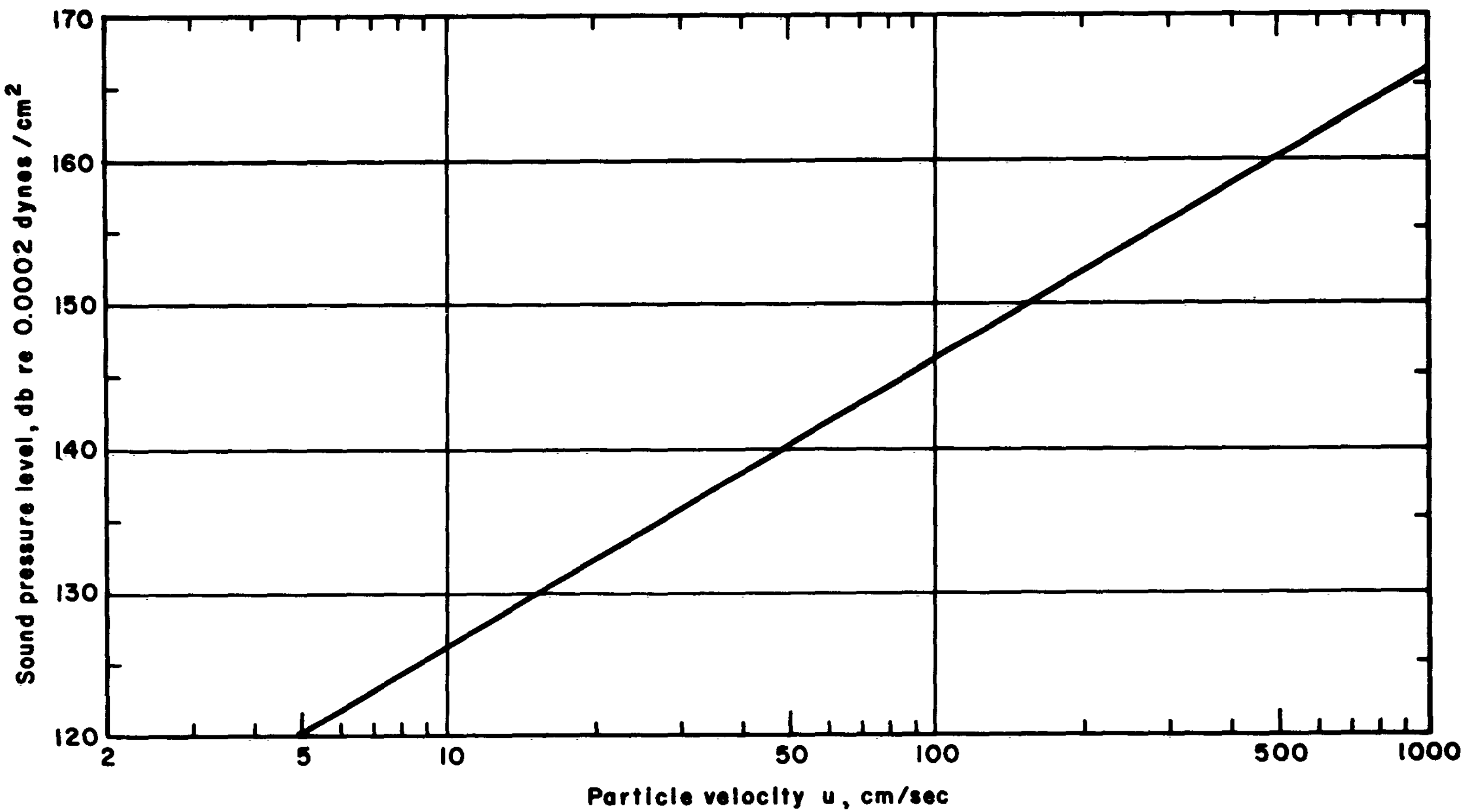


Figure 2. Variation of Sound Pressure Level with Particle Velocity

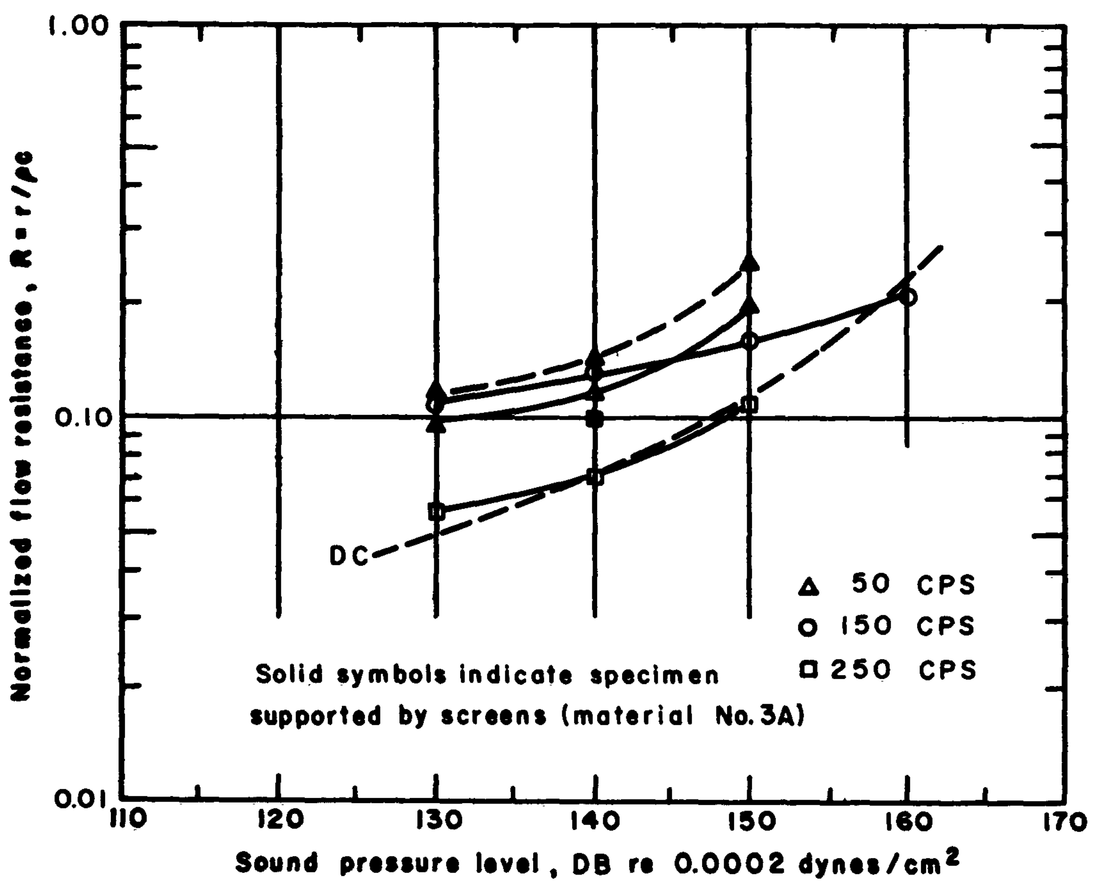


Figure 3. AC and DC Flow Resistance of Materials
(a) Material No. 3 (1/2"), Polyurethane Foam Etched, Low Frequencies, See Table I (a)

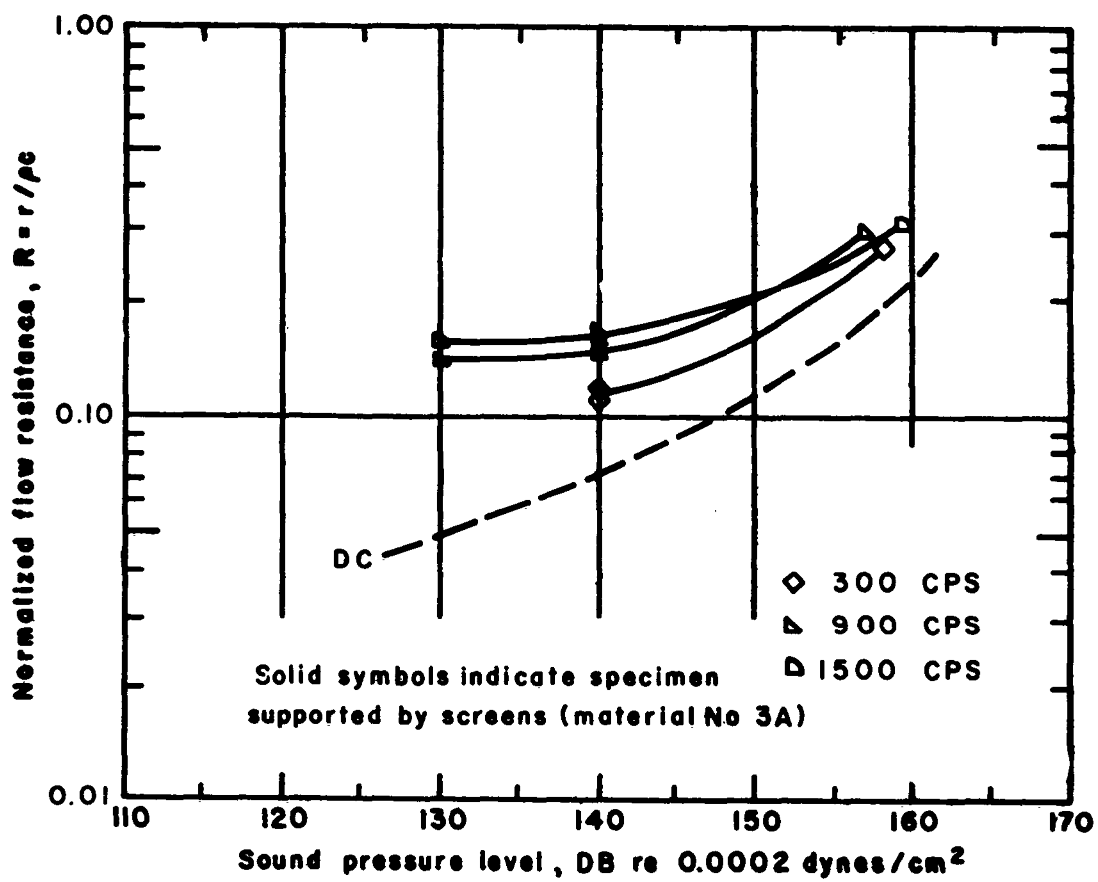


Figure 3. AC and DC Flow Resistance of Materials
(b) Material No. 3 (1/2"), Polyurethane Foam Etched, Medium Frequencies, See Table I (a)

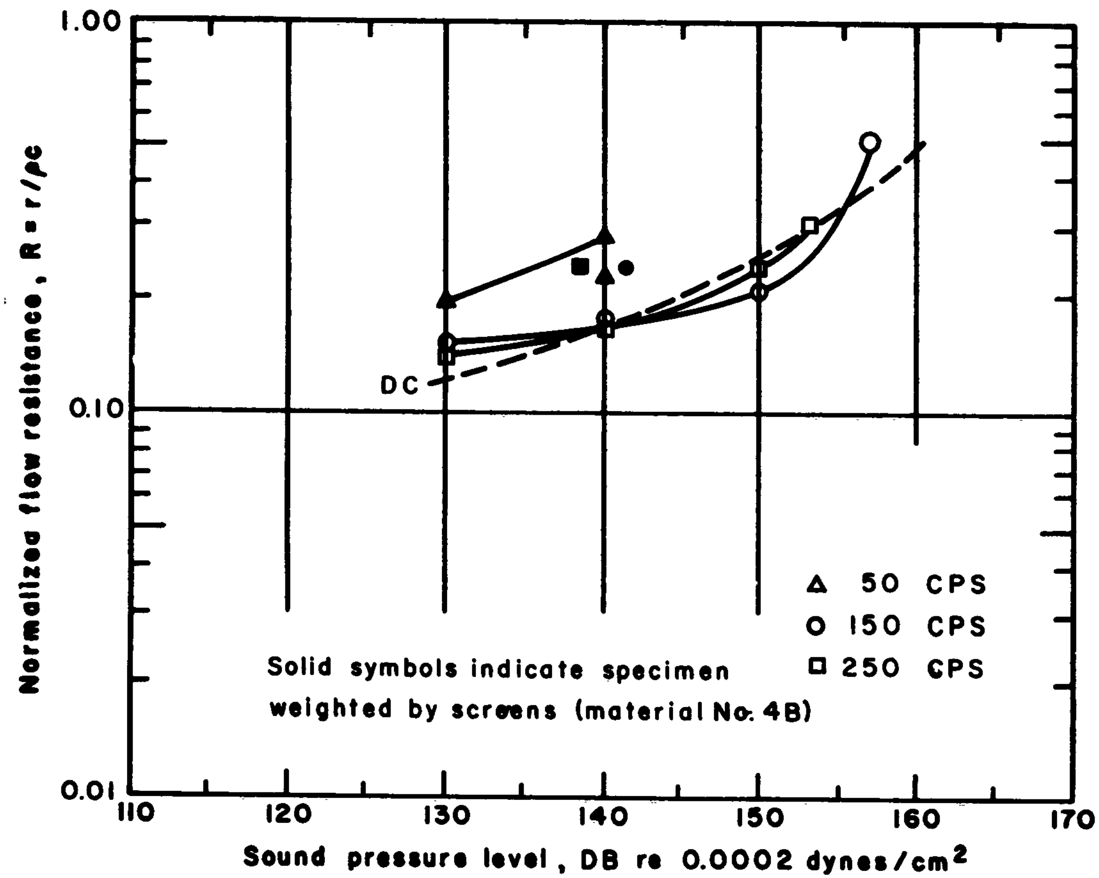


Figure 3. AC and DC Flow Resistance of Materials
(c) Material No. 4 (1/2"), Polyurethane Foam Etched, Low Frequencies, See Table I (a)

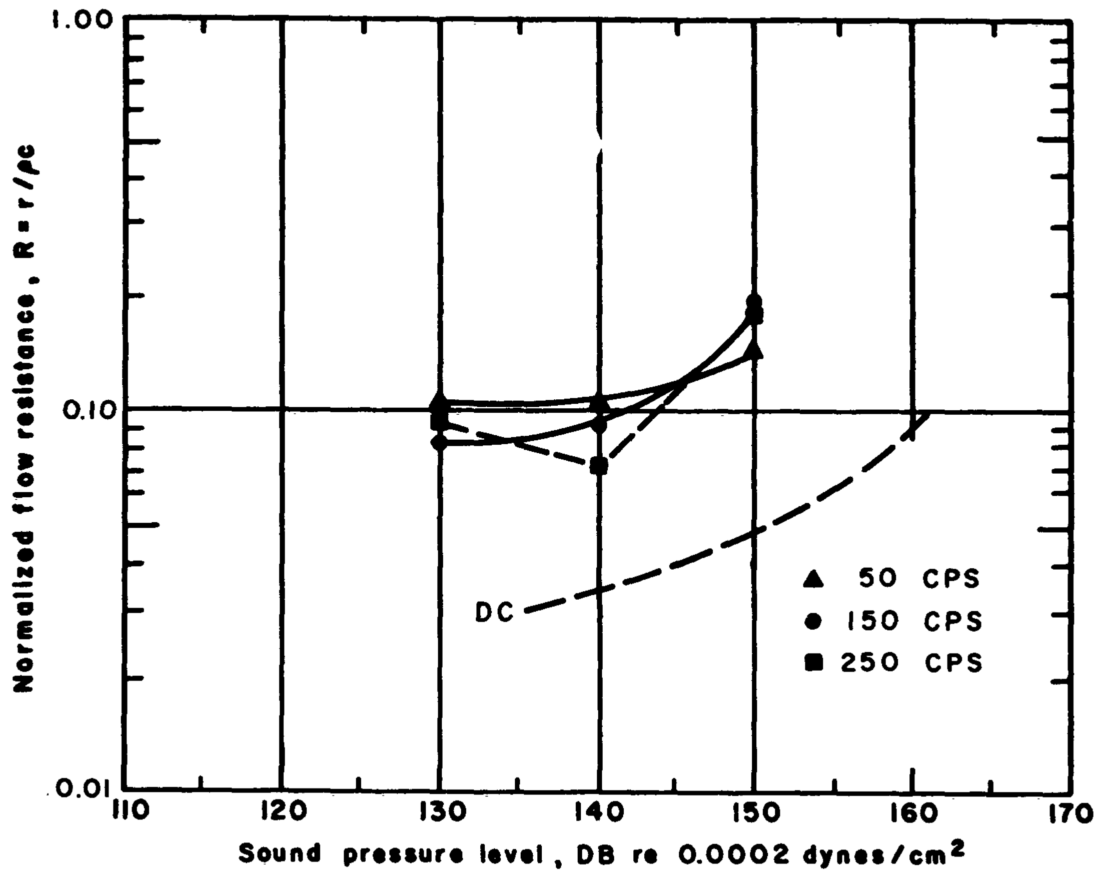


Figure 3. AC and DC Flow Resistance of Materials
(d) Material No. 5A, 100 Mesh Wire Screen, Low Frequencies, See Table I (c)

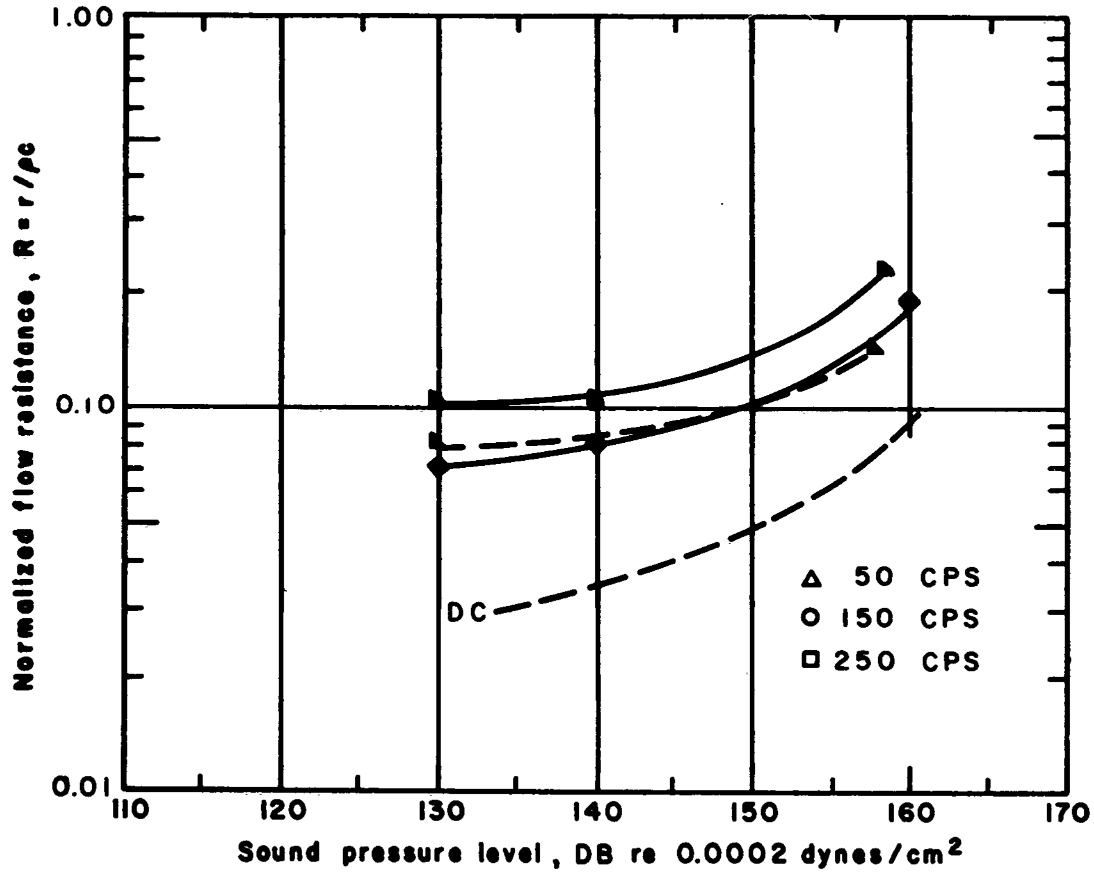


Figure 3. AC and DC Flow Resistance of Materials
(e) Material No. 5A 100 Mesh Wire Screen, Medium Frequencies, See Table I (c)

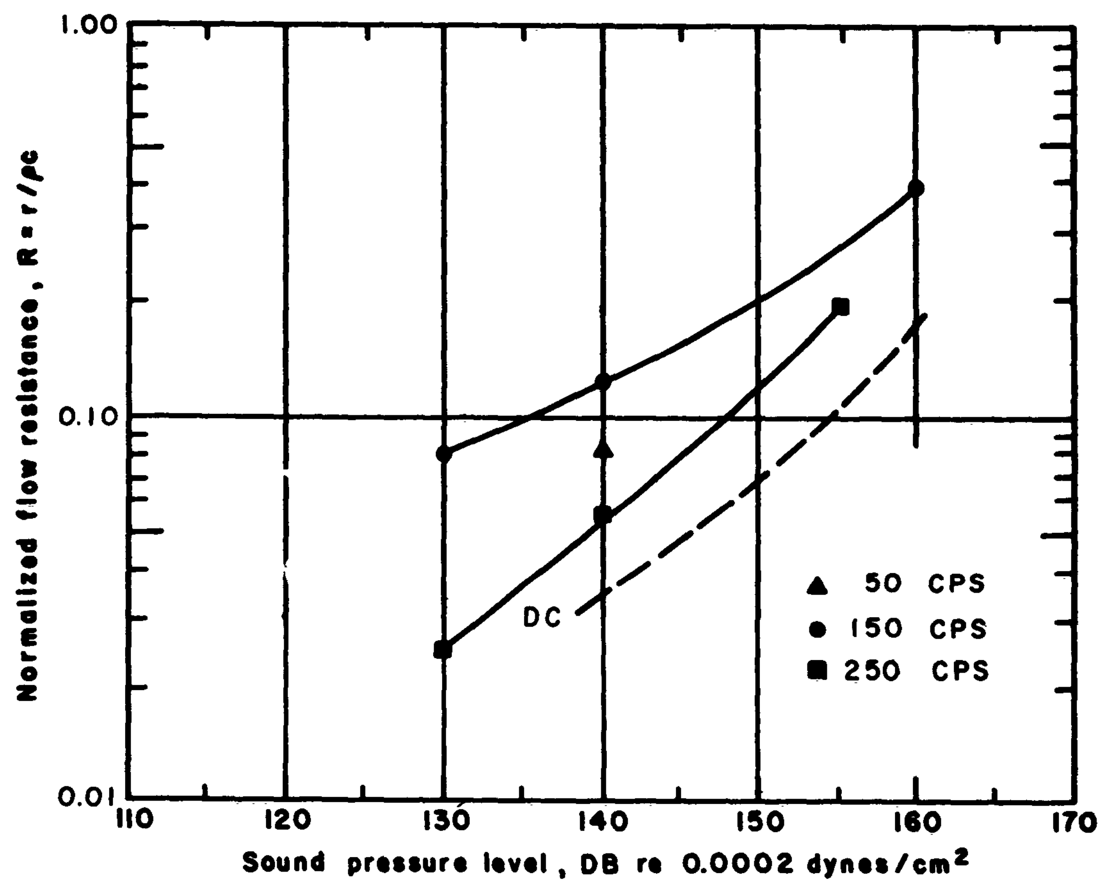


Figure 3. AC and DC Flow Resistance of Materials
(f) Material No. 1A Woven Glass Cloth, 2 Layers, See Table I (d)

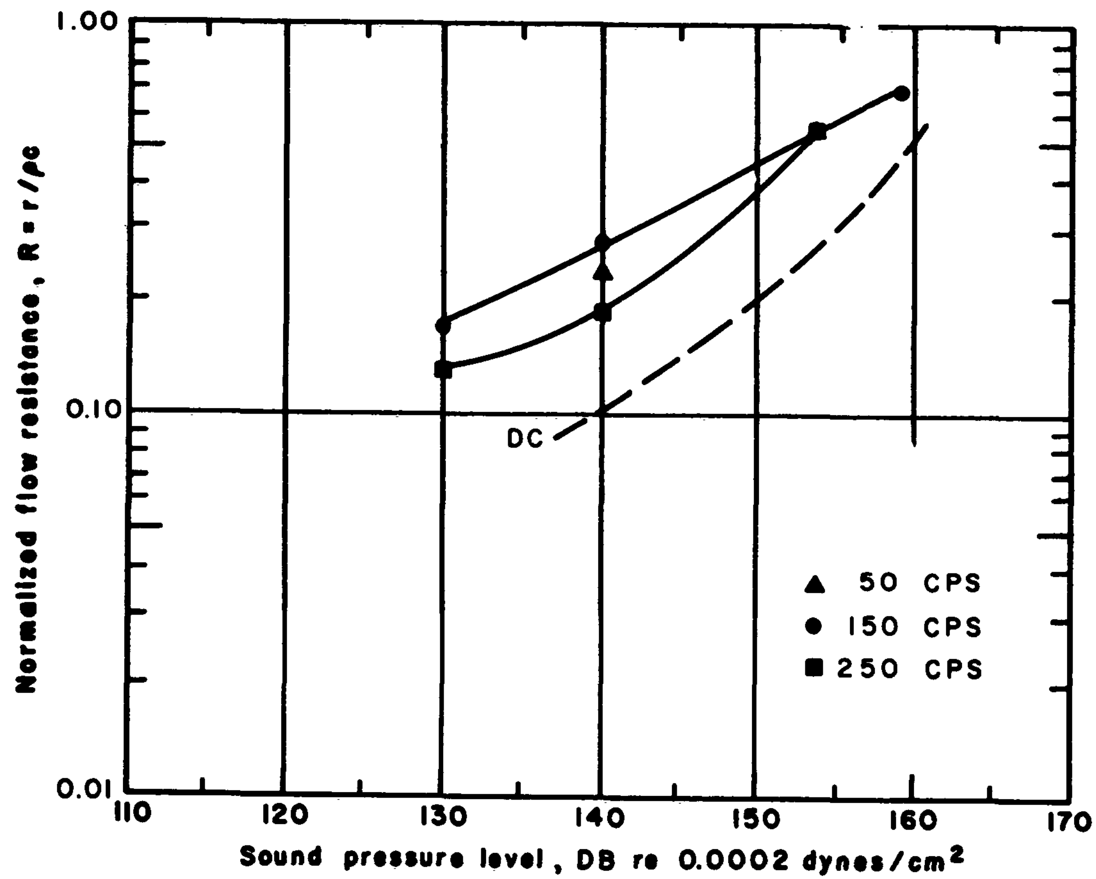


Figure 3. AC and DC Flow Resistance of Materials
(g) Material No. 4A Woven Glass Cloth, 2 Layers, See Table I (d)

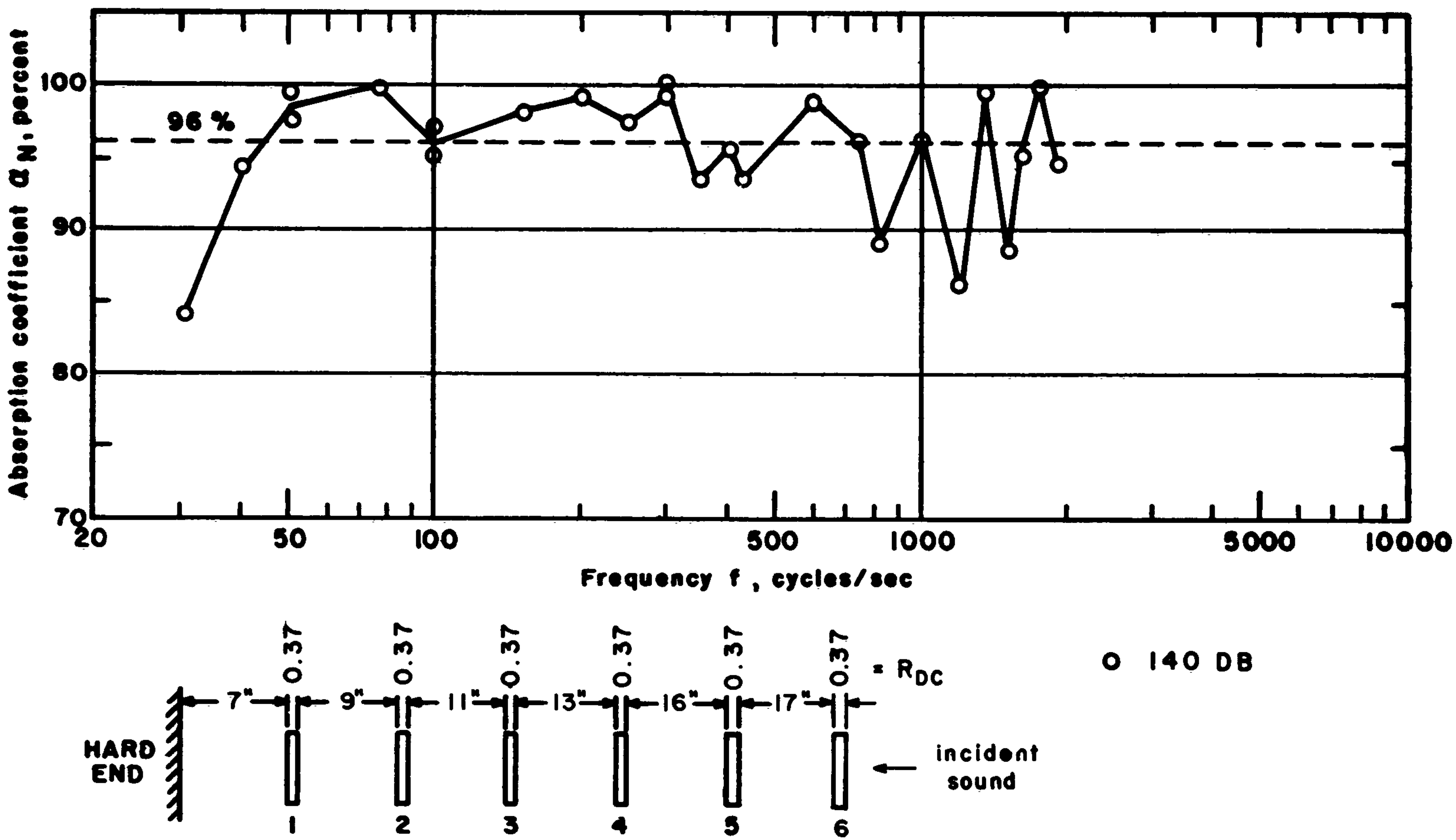


Figure 4. Absorption Coefficients for Layer Systems
(a) System No. 1 See Table III (a)

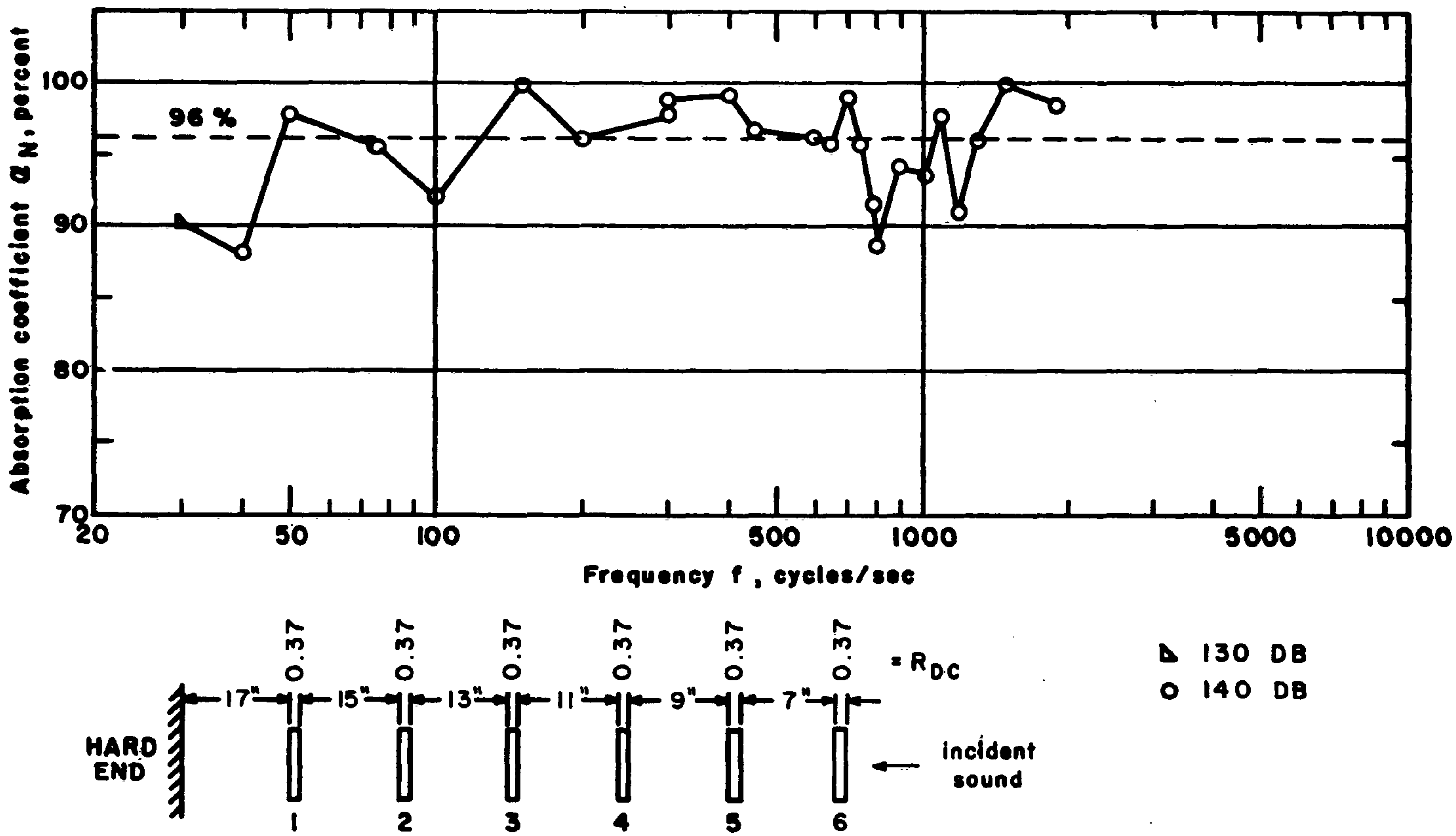


Figure 4. Absorption Coefficients for Layer Systems
(b) System No. 2 See Table III (a)

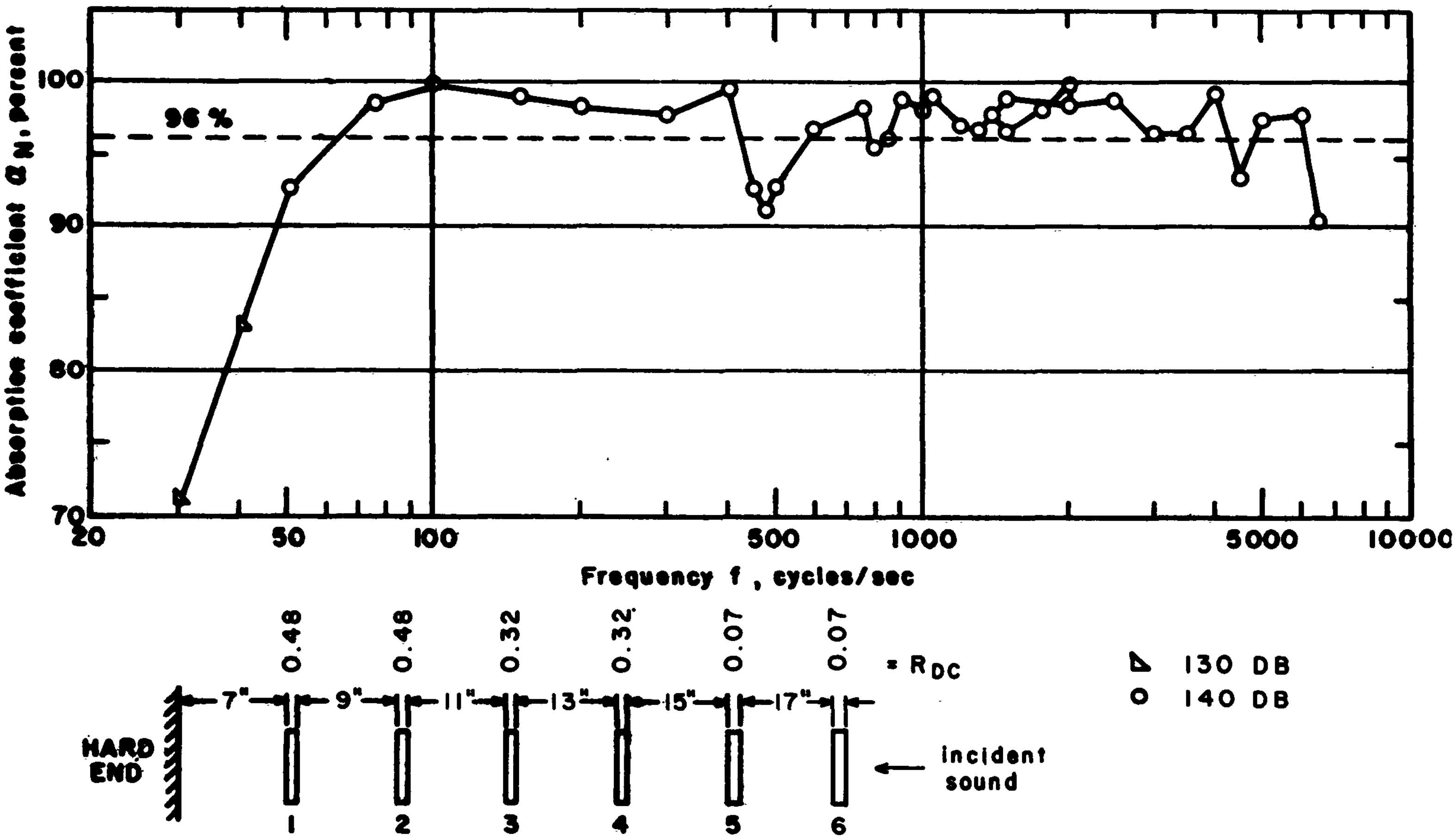


Figure 4. Absorption Coefficients for Layer Systems
(c) System No. 3 See Table III (a)

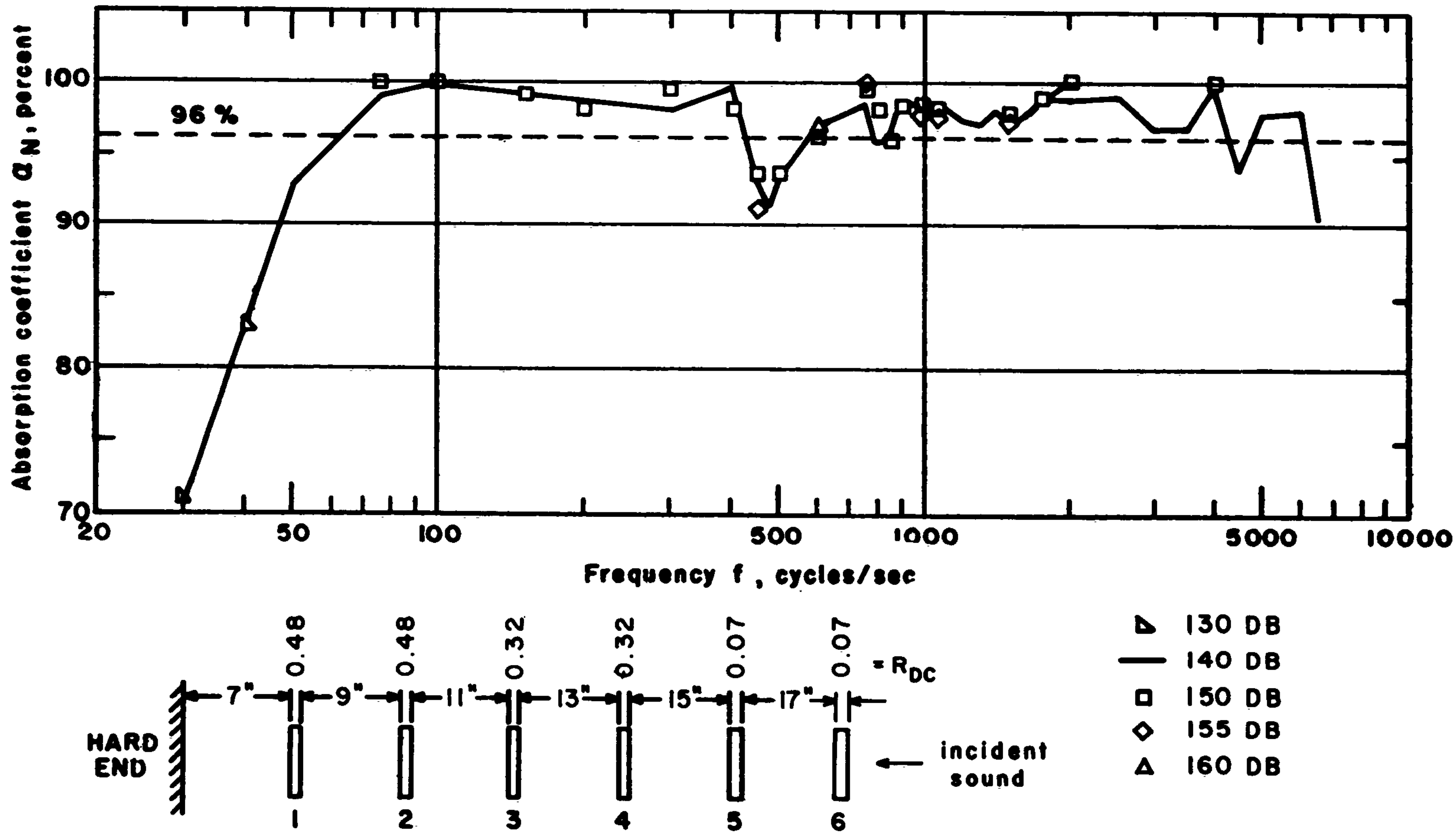


Figure 4. Absorption Coefficients for Layer Systems
(d) System No. 3, 130 to 160 db, See Table III (a)

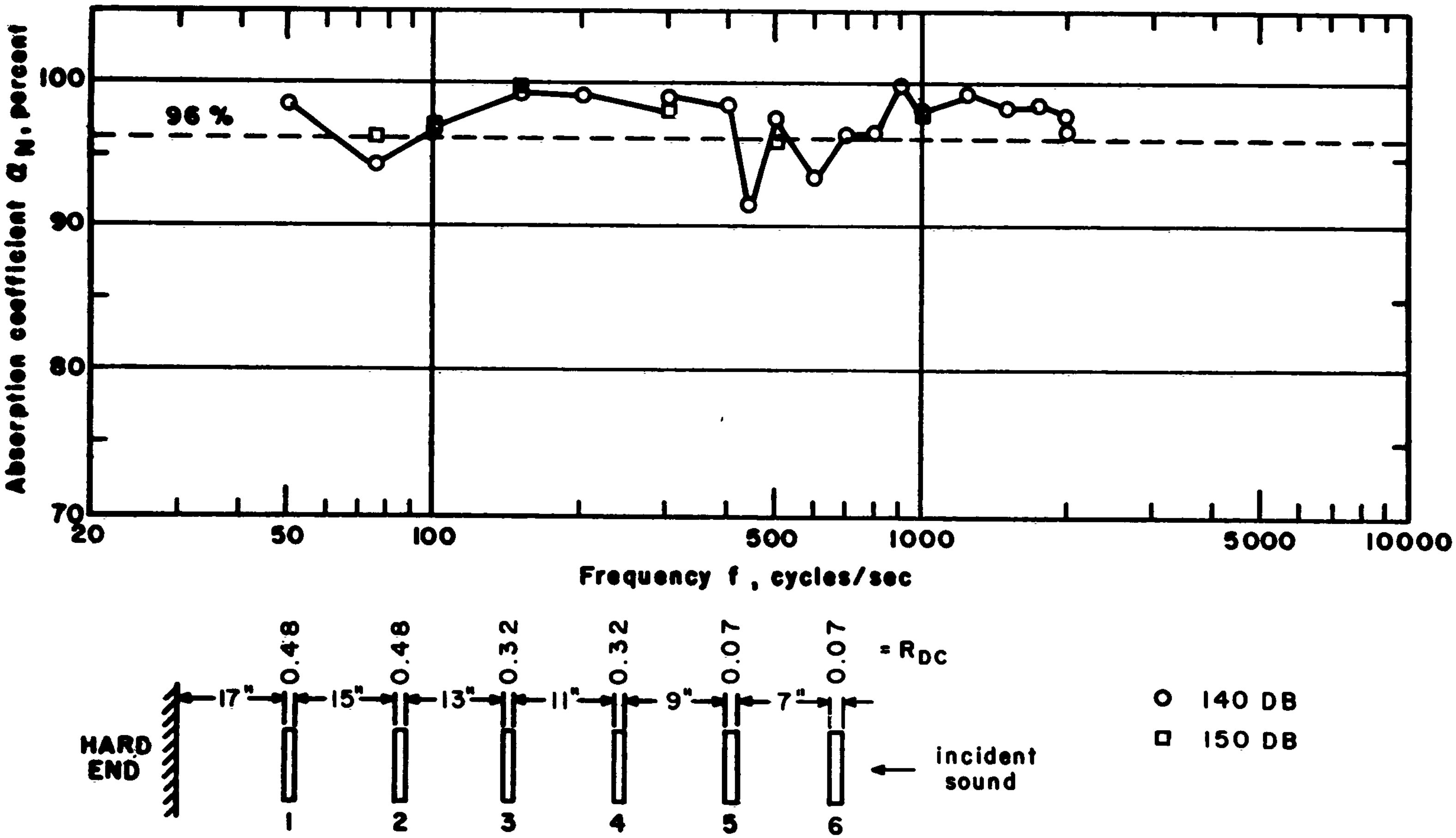


Figure 4. Absorption Coefficients for Layer Systems
(e) System No. 4 See Table III (a)

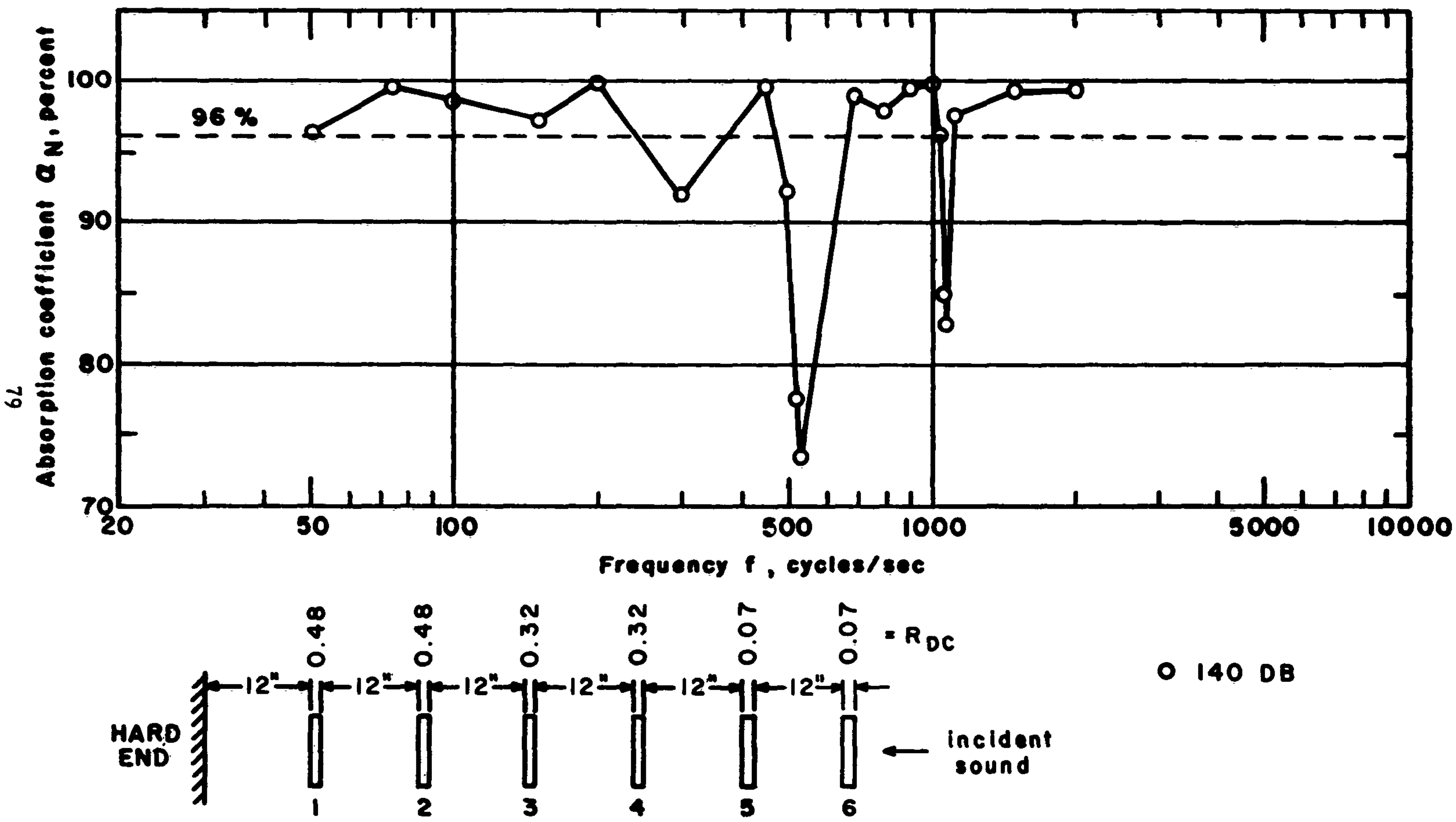


Figure 4. Absorption Coefficients for Layer Systems
(f) System No. 5 See Table III (b)

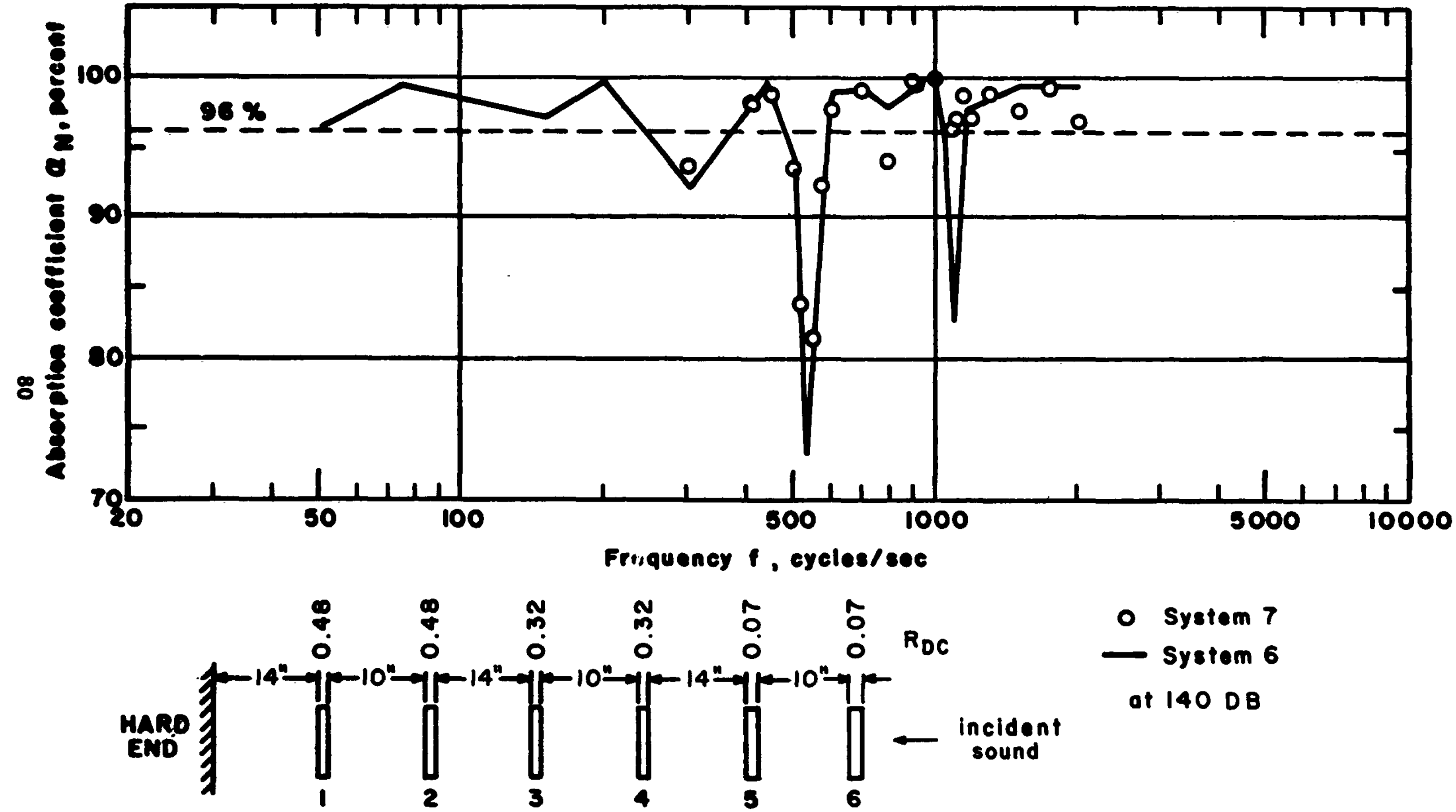


Figure 4. Absorption Coefficients for Layer Systems
(g) System No. 6 See Table III

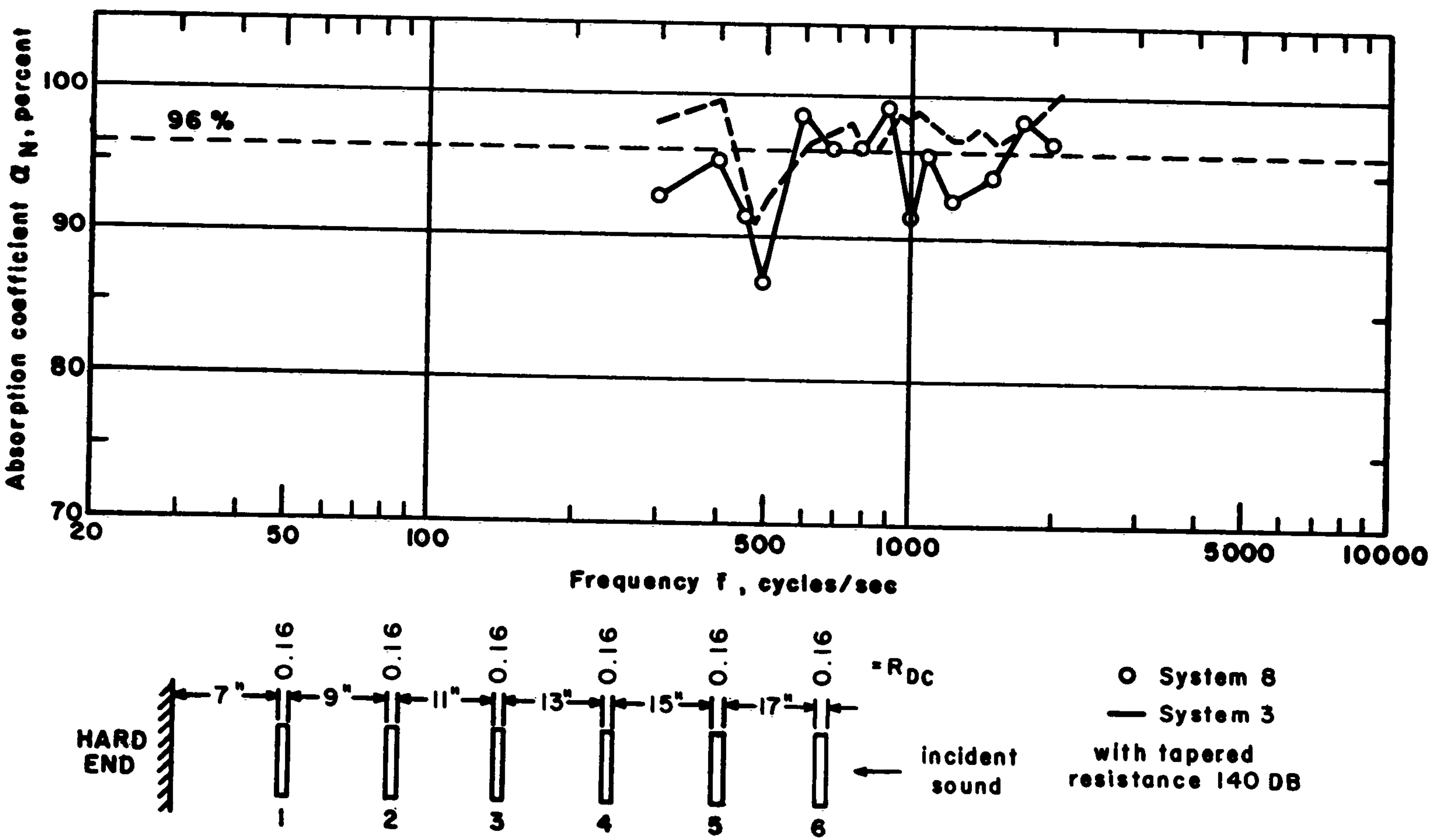


Figure 4. Absorption Coefficients for Layer Systems
(h) System No. 7 See Table III (a), (b)

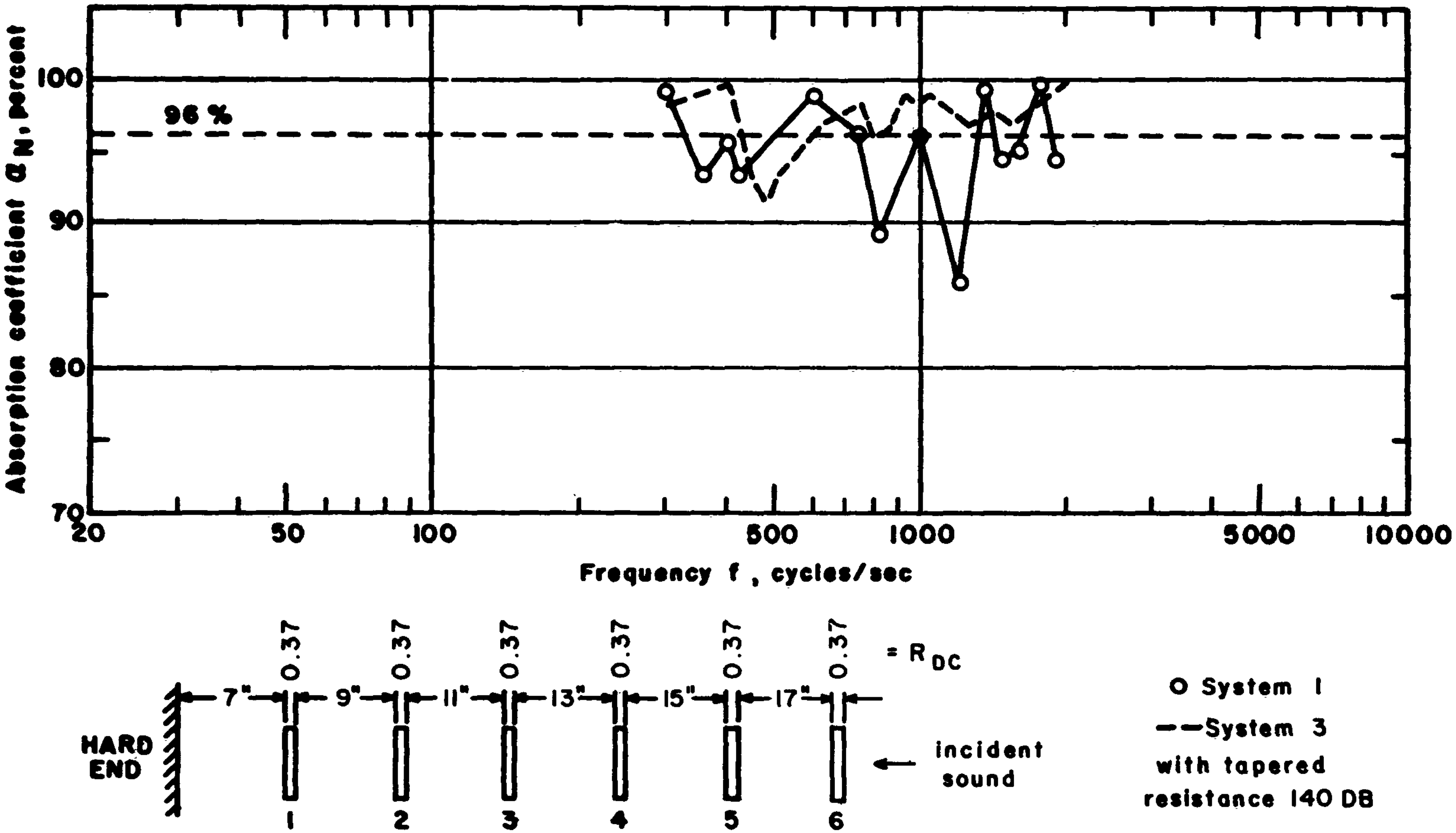


Figure 4. Absorption Coefficients for Layer Systems
(i) Systems No. 1 and 3 See Table III (a)

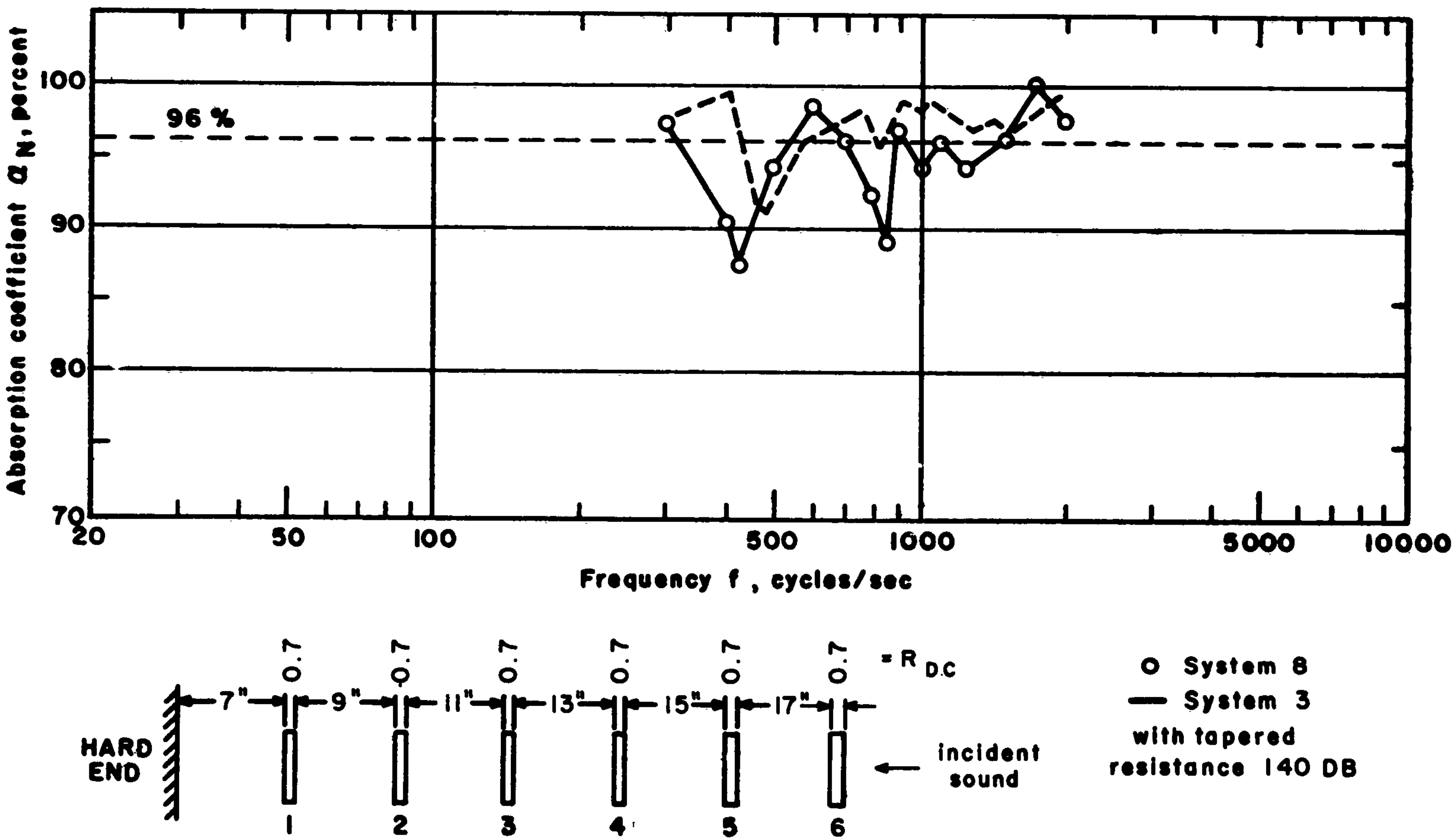


Figure 4. Absorption Coefficients for Layer Systems
(j) System No. 8 See Table III (a), (b)

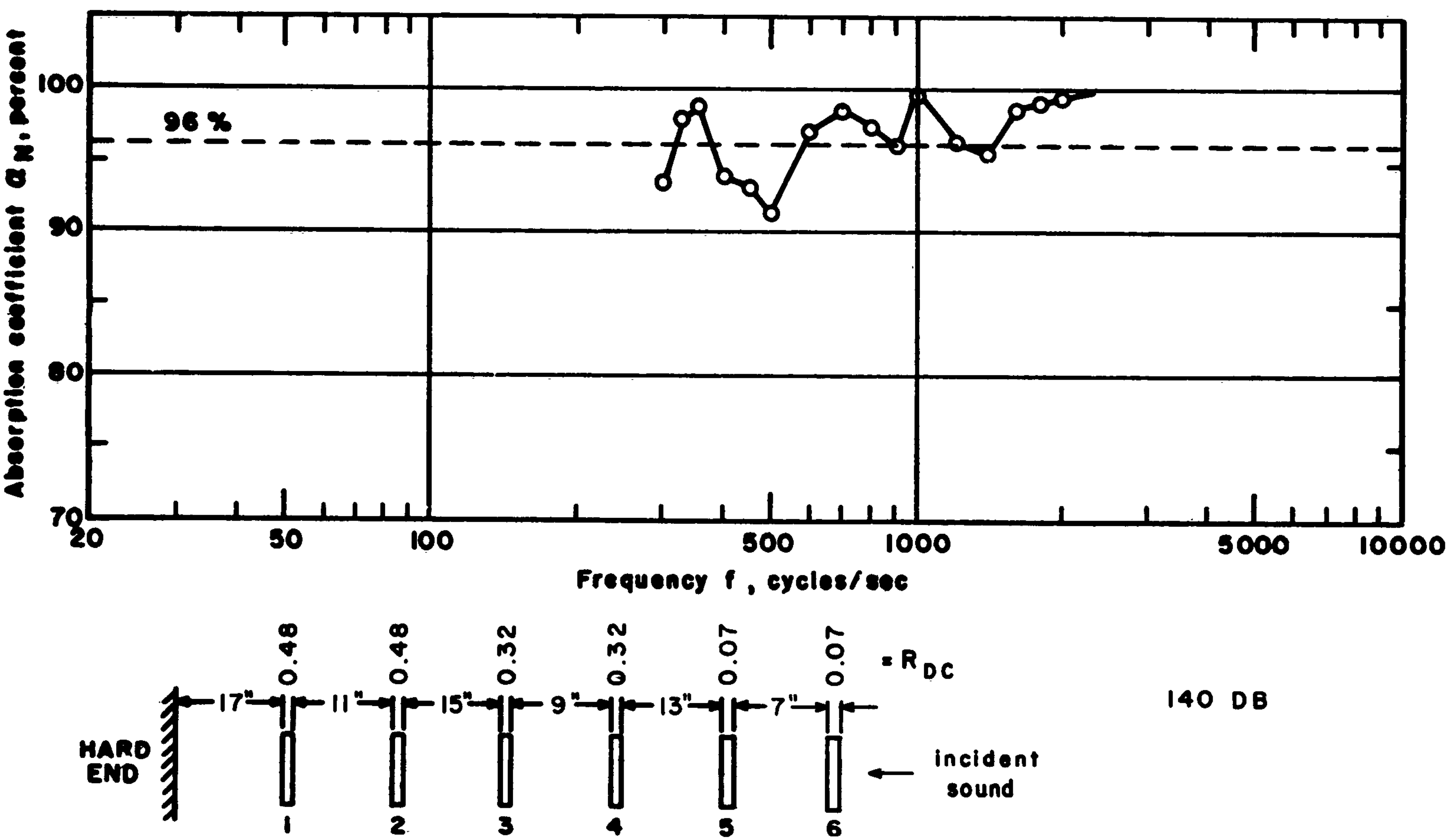


Figure 4. Absorption Coefficients for Layer Systems
(k) System No. 9 See Table III (c)

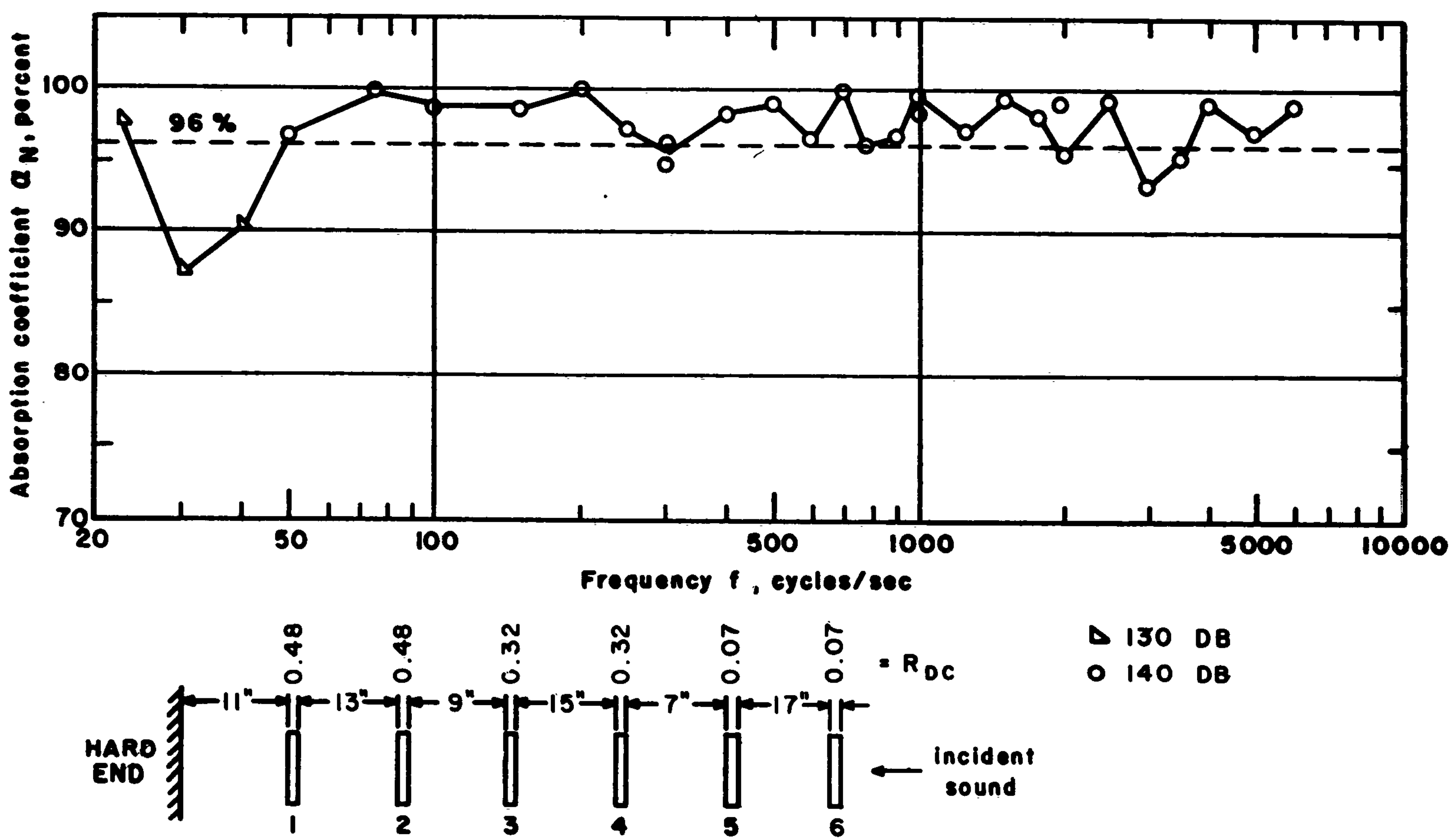


Figure 4. Absorption Coefficients for Layer Systems
(ℓ) System No. 10 See Table III (c)

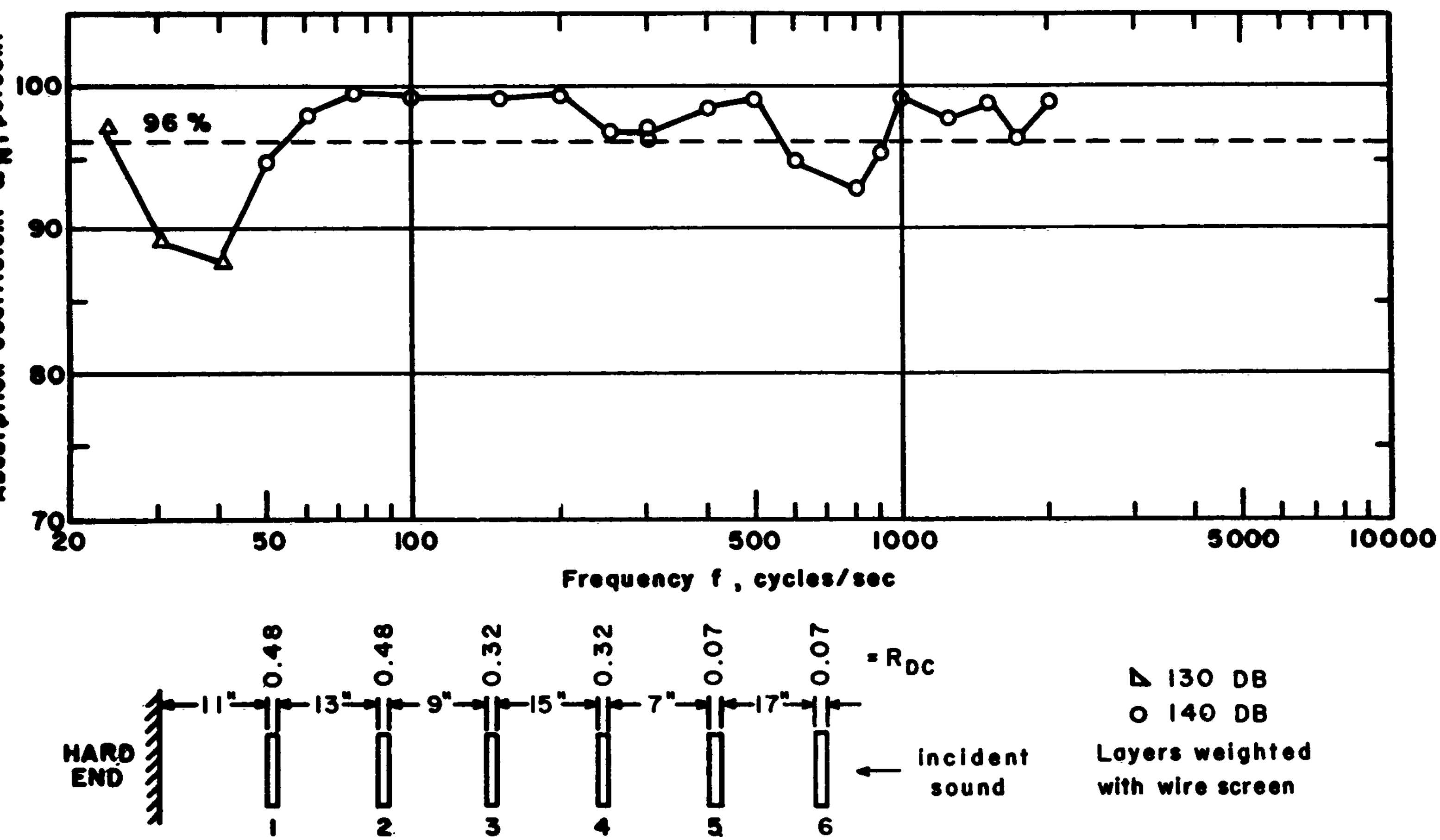


Figure 4. Absorption Coefficients for Layer Systems
(m) System No. 11 See Table III (c)

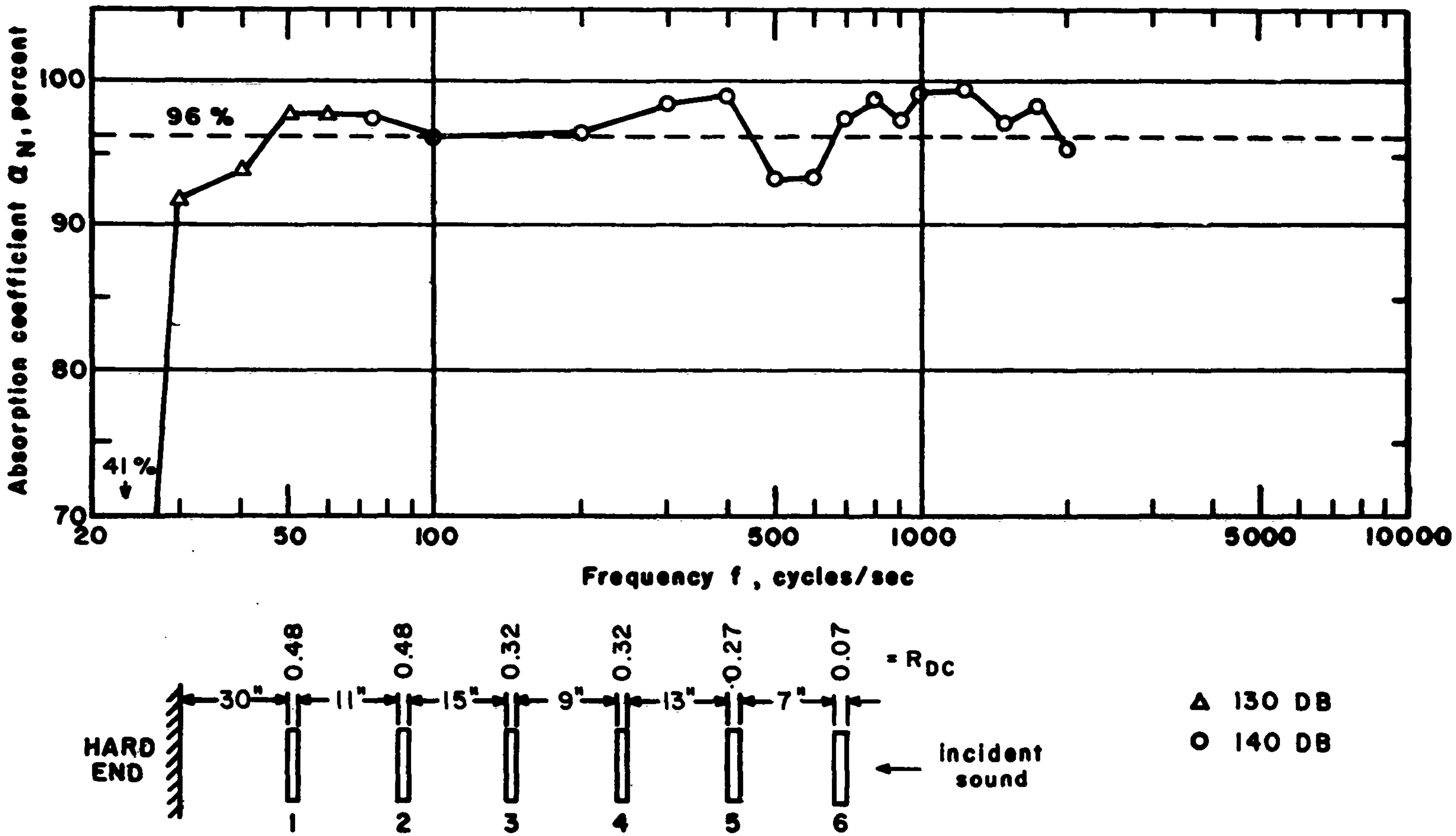


Figure 4. Absorption Coefficients for Layer Systems
(n) System No. 14 See Table III (d)

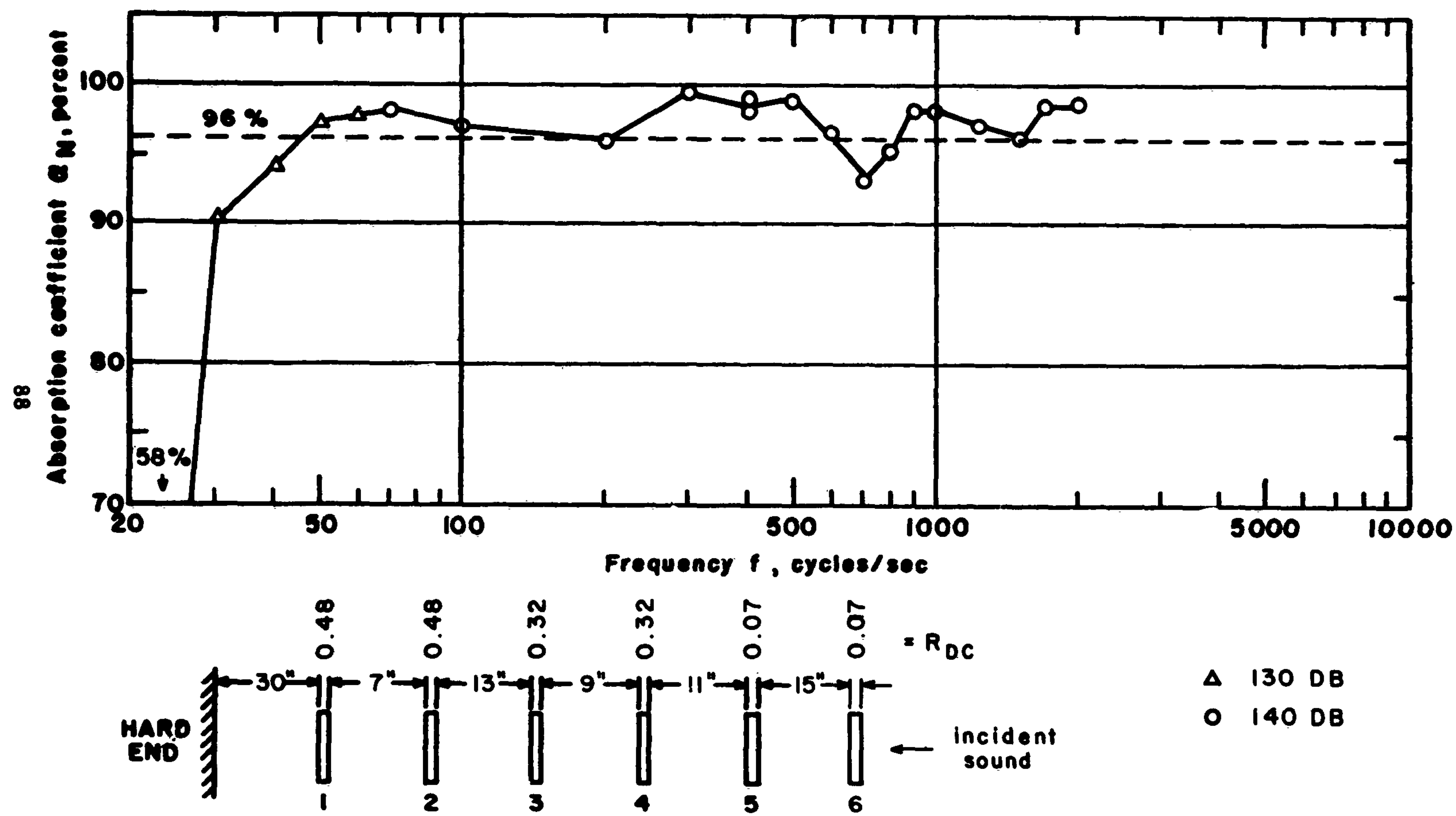


Figure 4. Absorption Coefficients for Layer Systems
(o) System No. 15 See Table III (d)

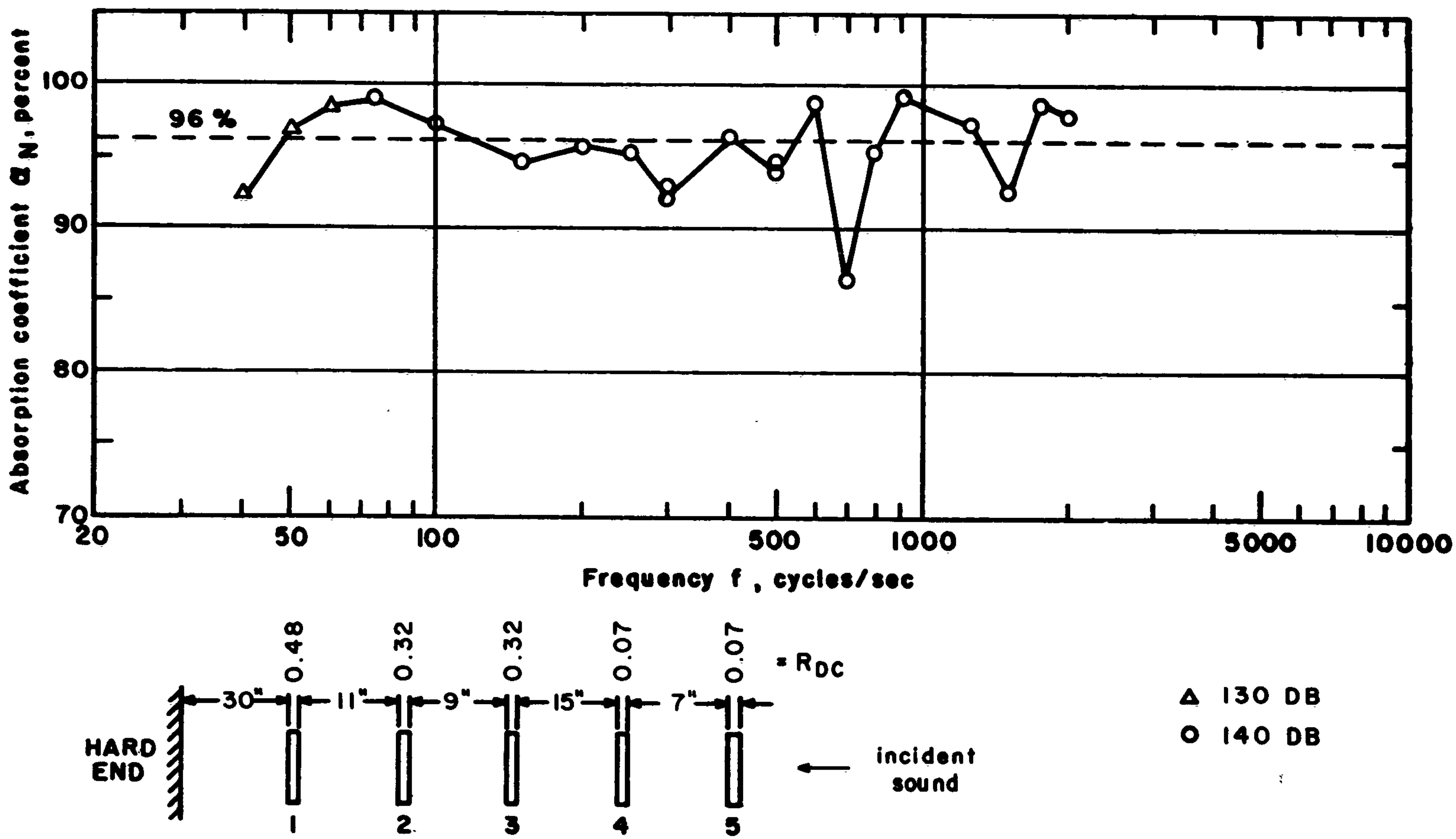


Figure 4. Absorption Coefficients for Layer Systems
(p) System No. 16 See Table III (d)

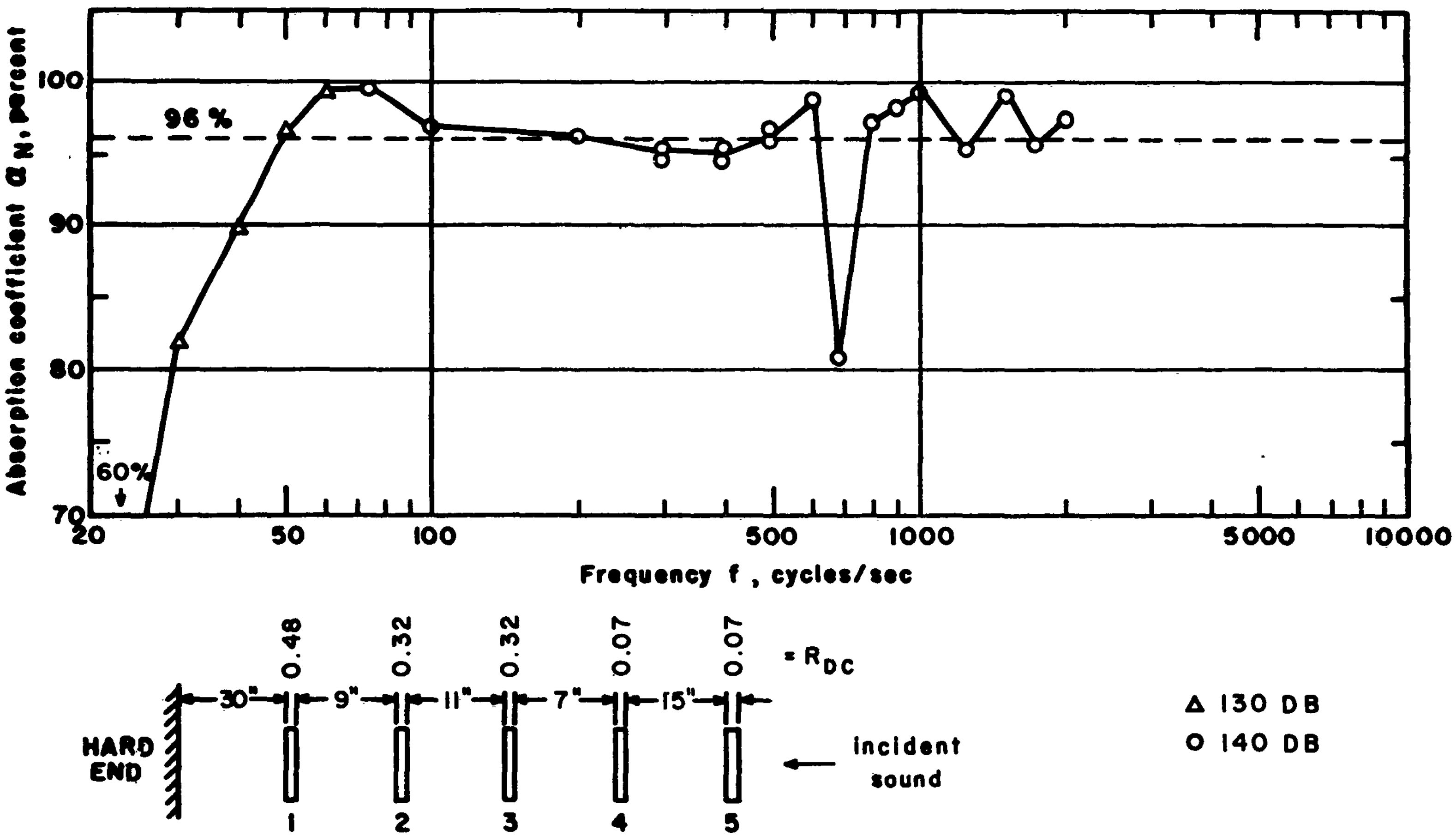


Figure 4. Absorption Coefficients for Layer Systems
(q) System No. 17 See Table III (d)

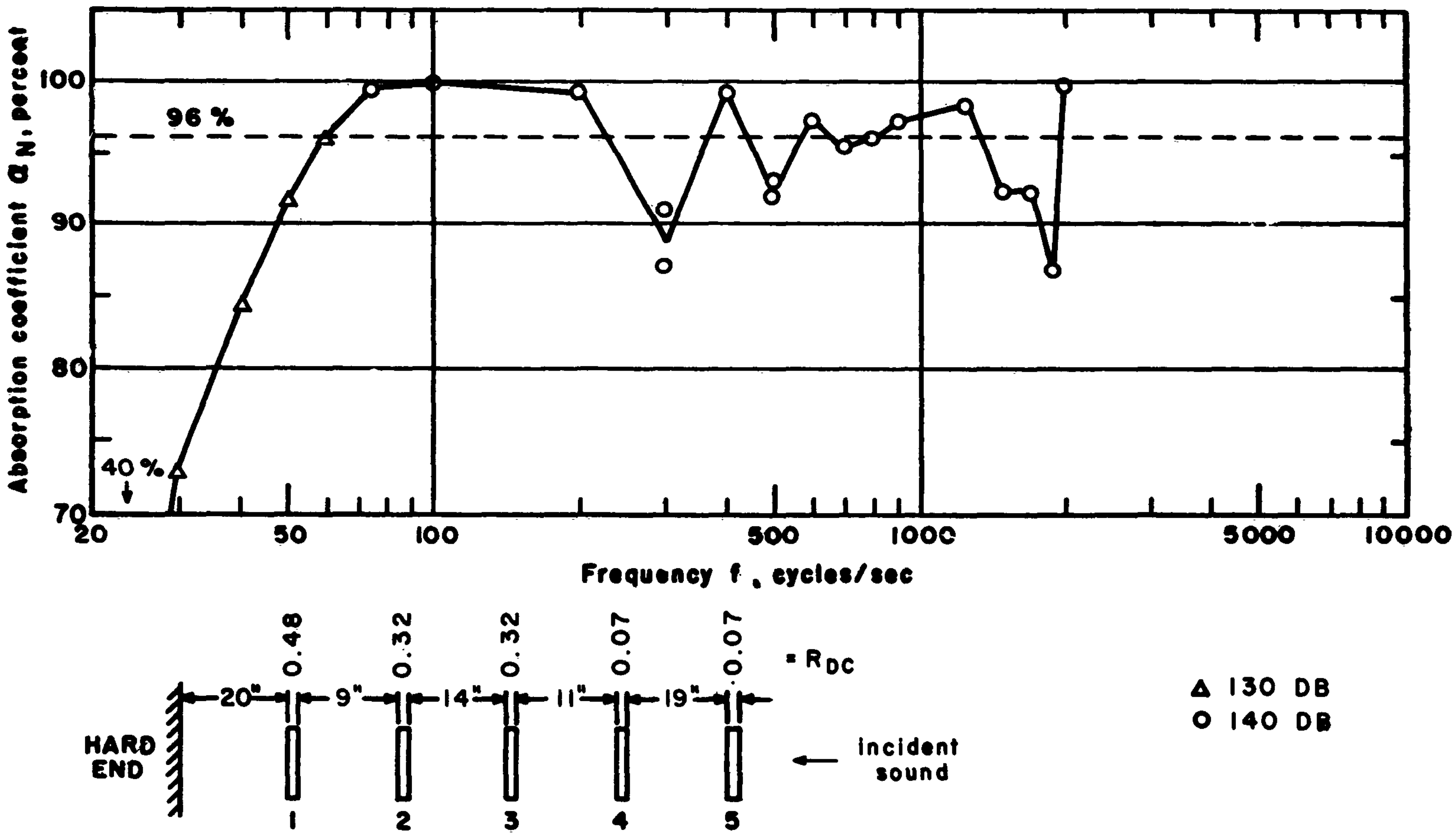


Figure 4. Absorption Coefficients for Layer Systems
(r) System No. 18 See Table III (e)

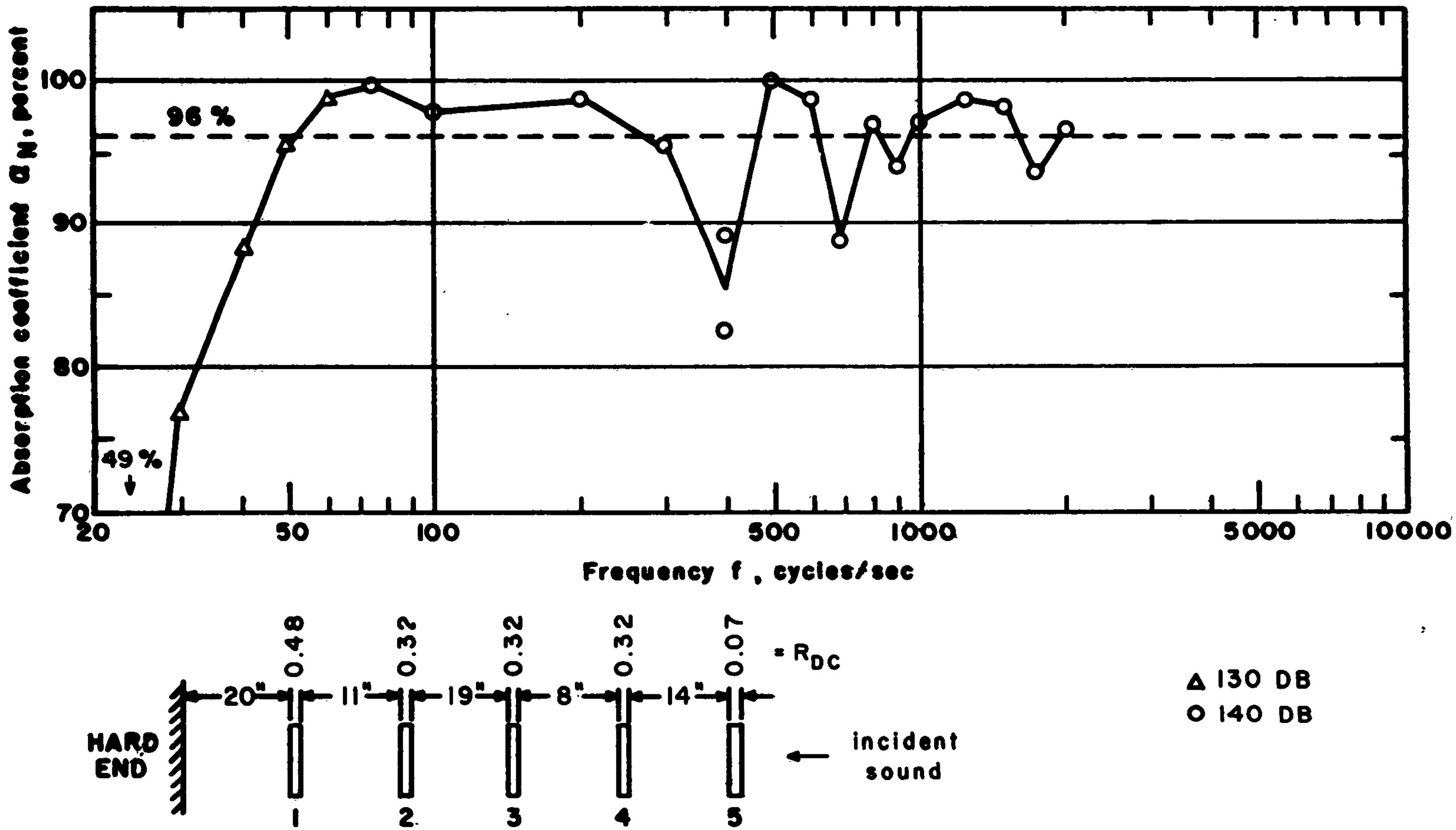


Figure 4. Absorption Coefficients for Layer Systems
(s) System No. 19 See Table III (e)

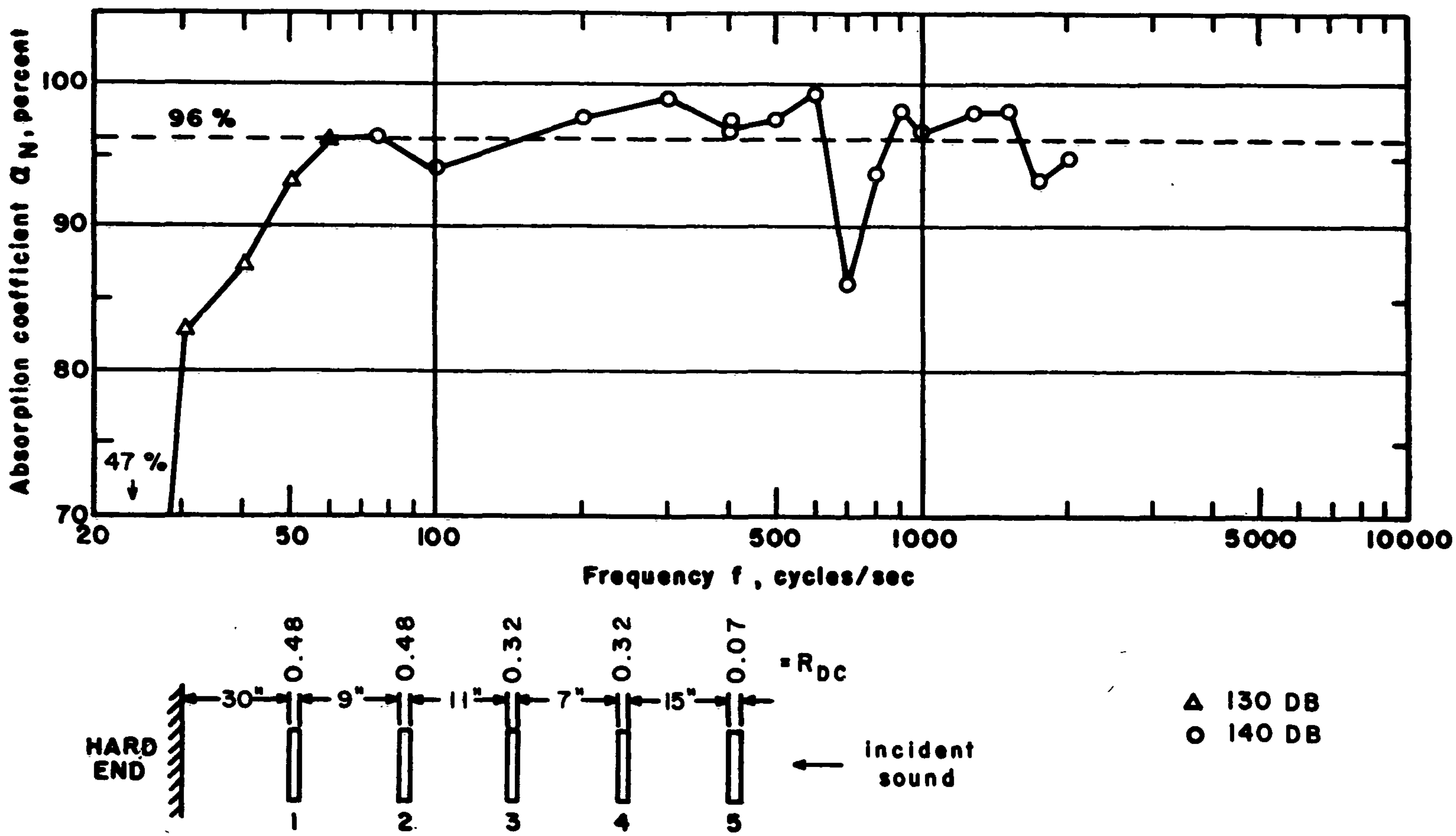


Figure 4. Absorption Coefficients for Layer Systems
(t) System No. 20 See Table III (e)

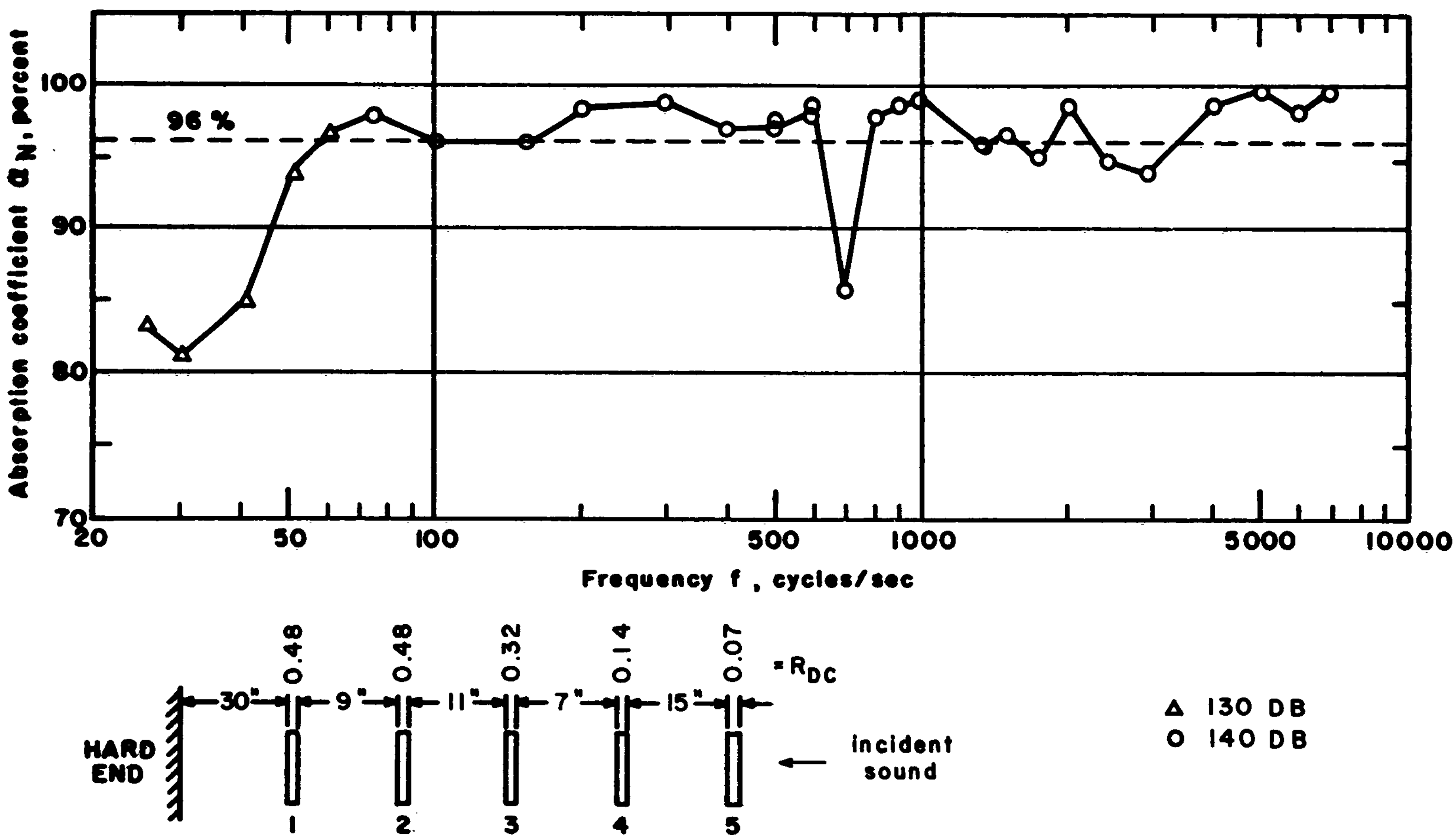


Figure 4. Absorption Coefficients for Layer Systems
(u) System No. 21 See Table III (e)

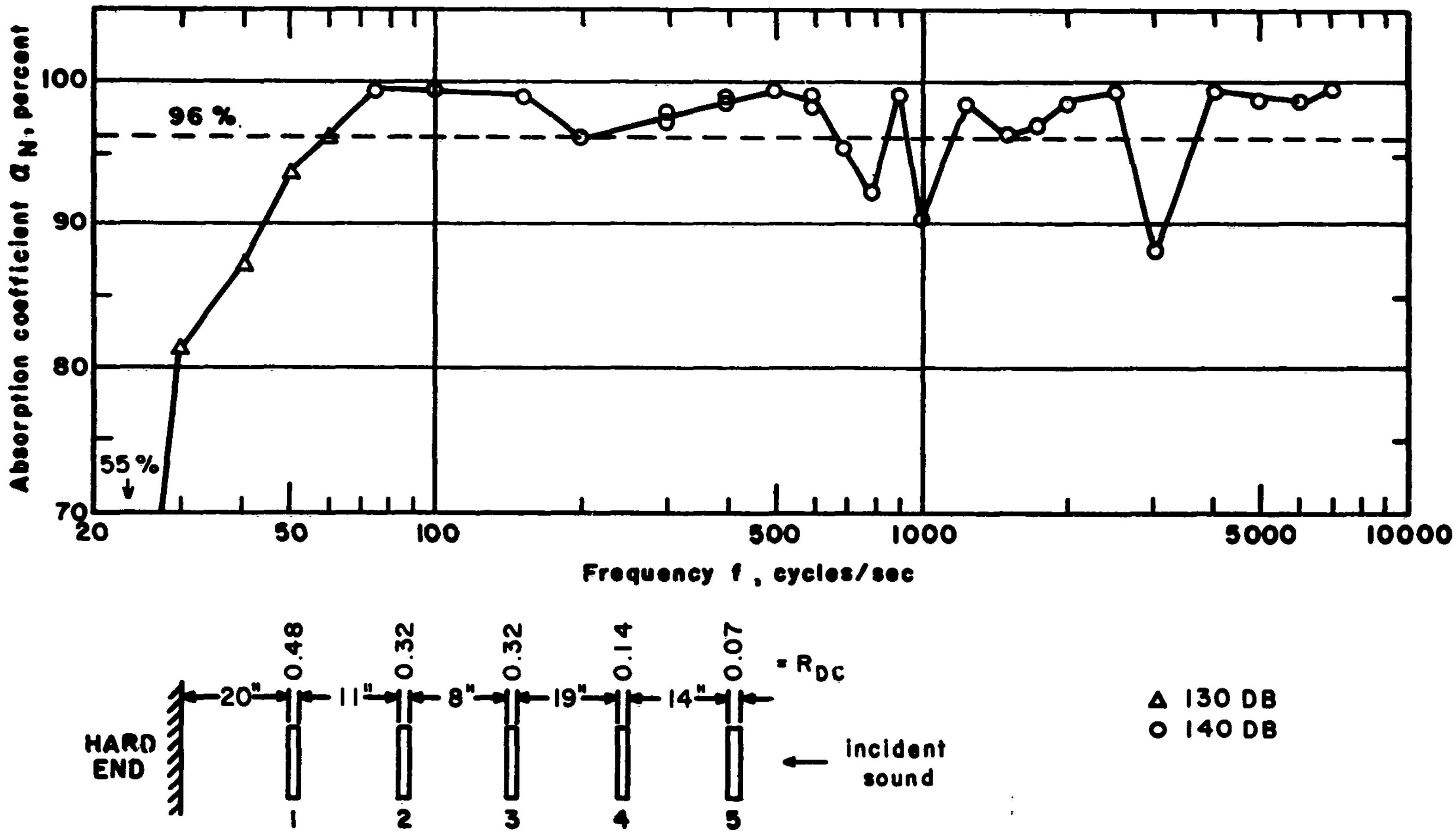


Figure 4. Absorption Coefficients for Layer Systems
(v) System No. 22 See Table III (f)

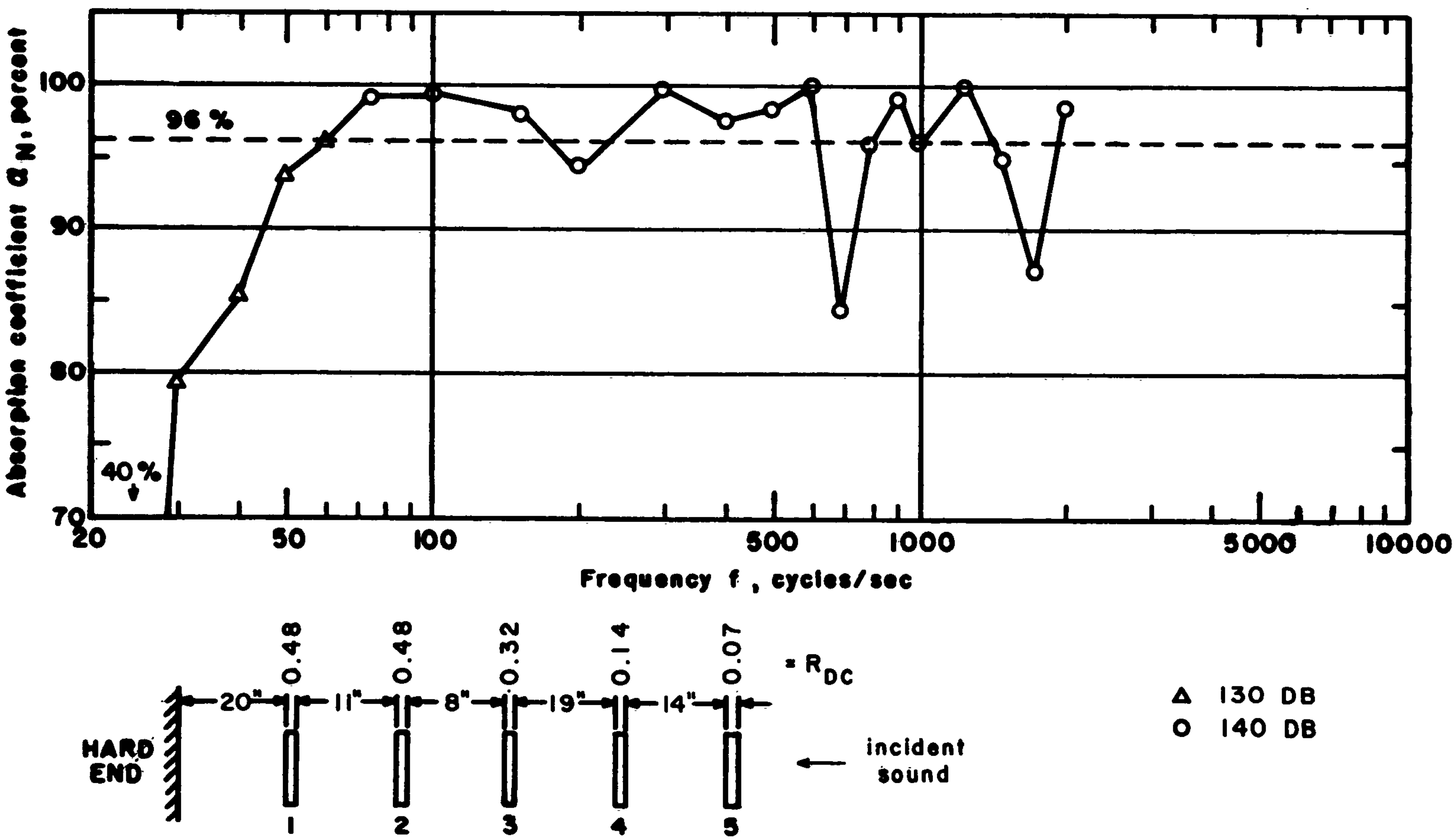


Figure 4. Absorption Coefficients for Layer Systems
(w) System No. 23 See Table III (f)

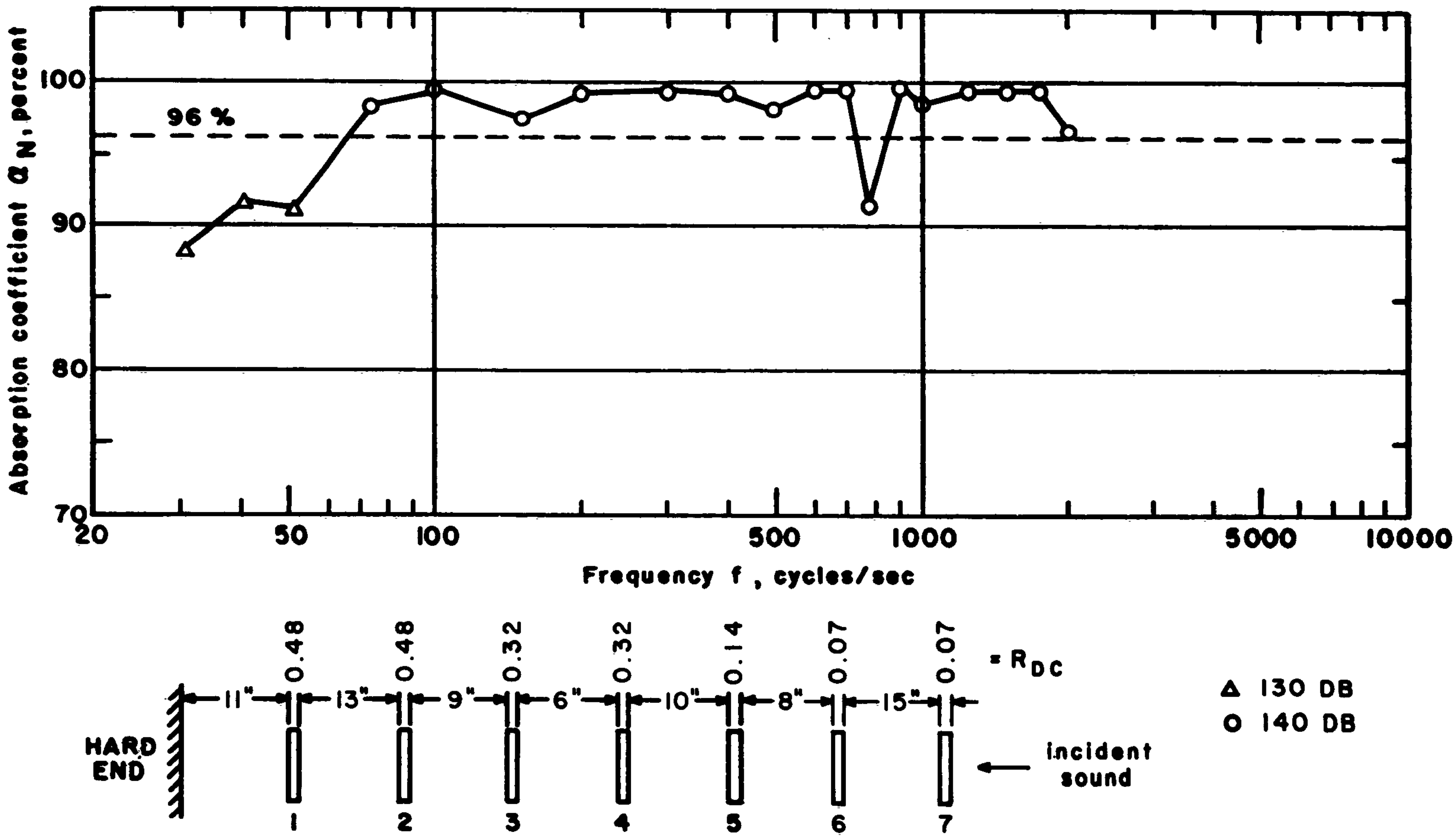


Figure 4. Absorption Coefficients for Layer Systems
(x) System No. 24 See Table III (f)

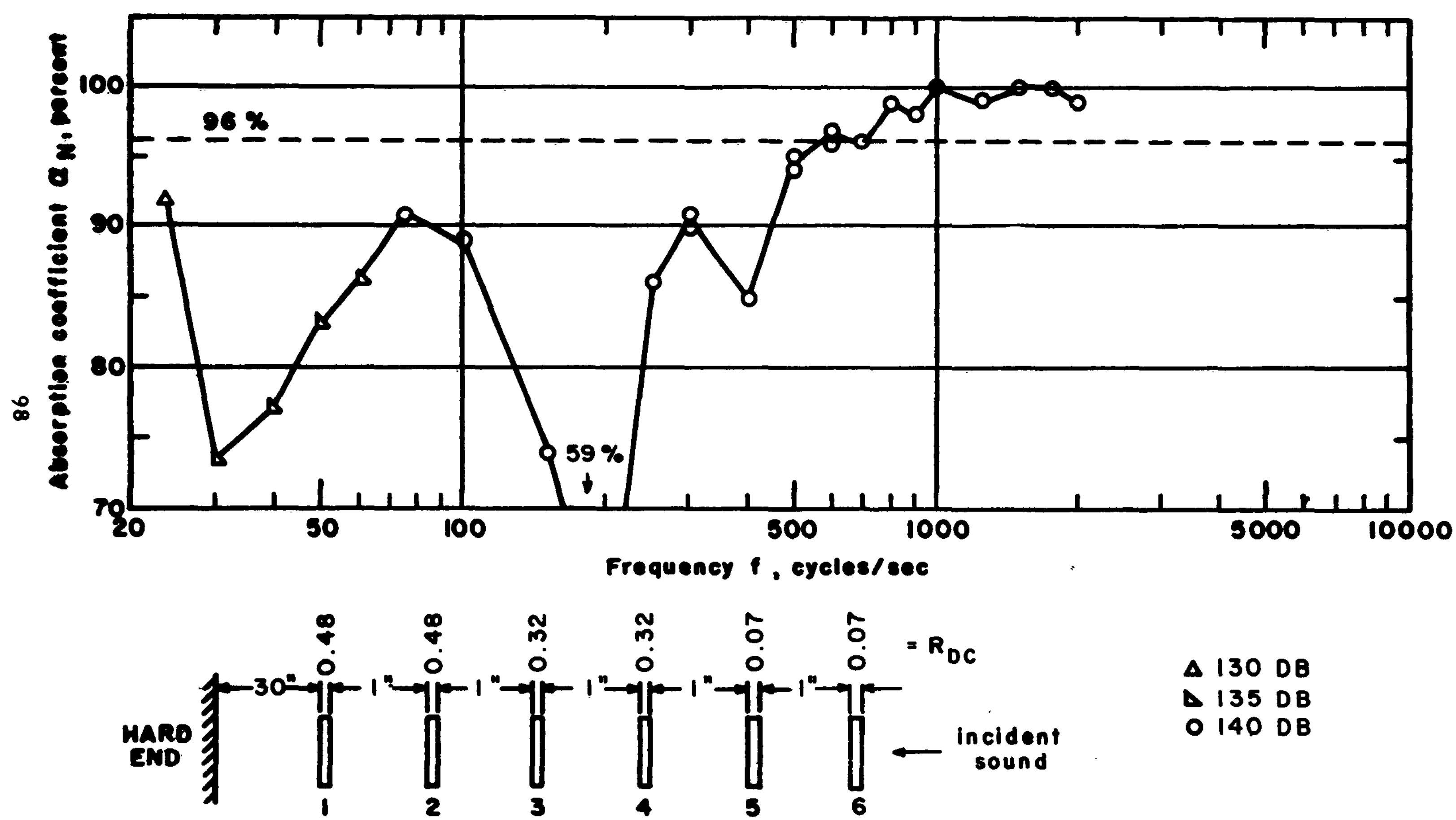


Figure 4. Absorption Coefficients for Layer Systems
(y) System No. 25 (System No. 11 Collapsed) See, Table III (f)

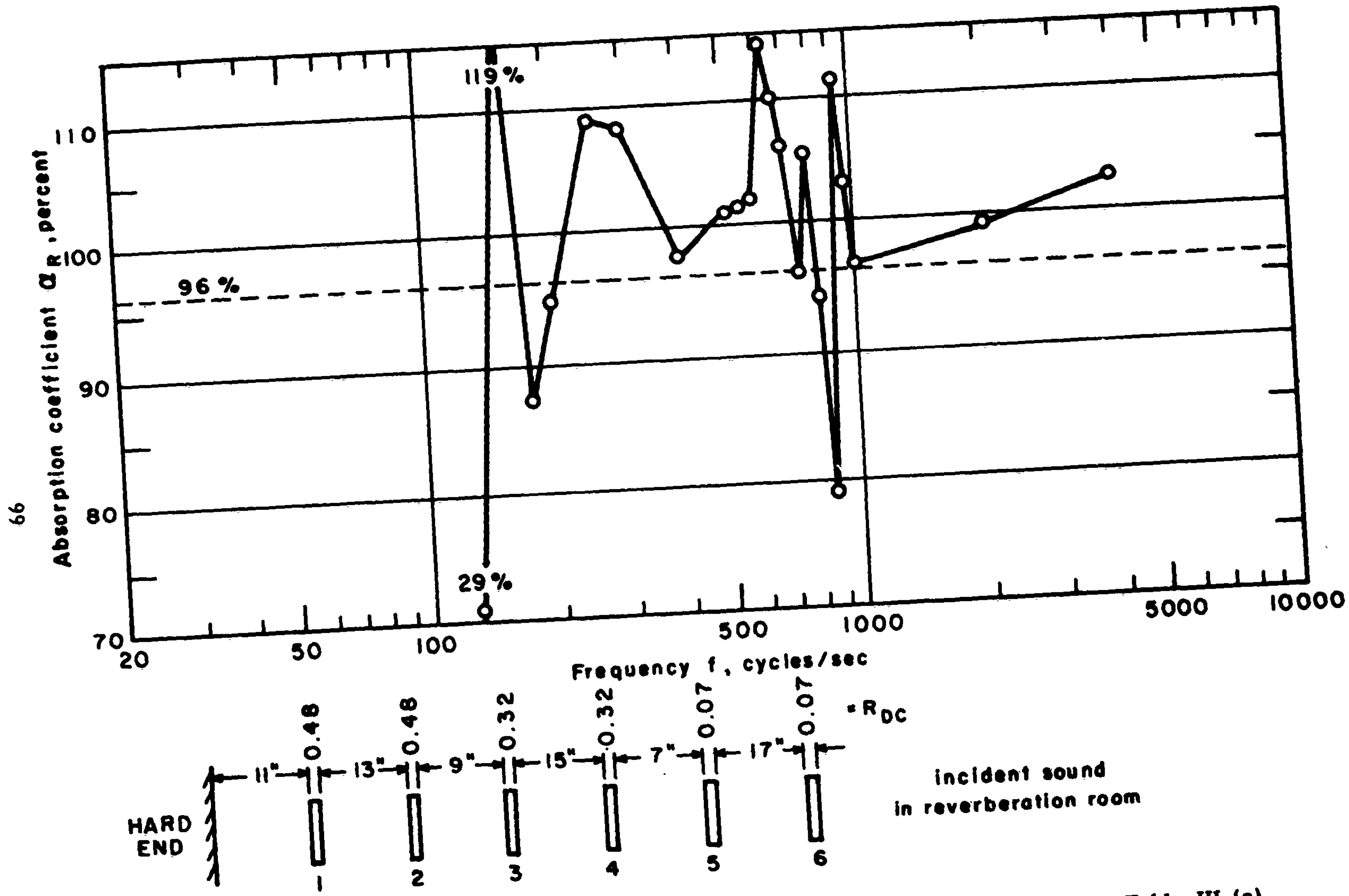


Figure 5. Random Incidence Absorption Coefficients for System No. 11 See Table III (c)

Figure 6. Damage from High Intensity Sound
(a) Fiberglas No. 3 (1/2") after Impedance Tests

Figure 6. Damage from High Intensity Sound
(b) Fibermetal No. 7 after
Impedance Tests

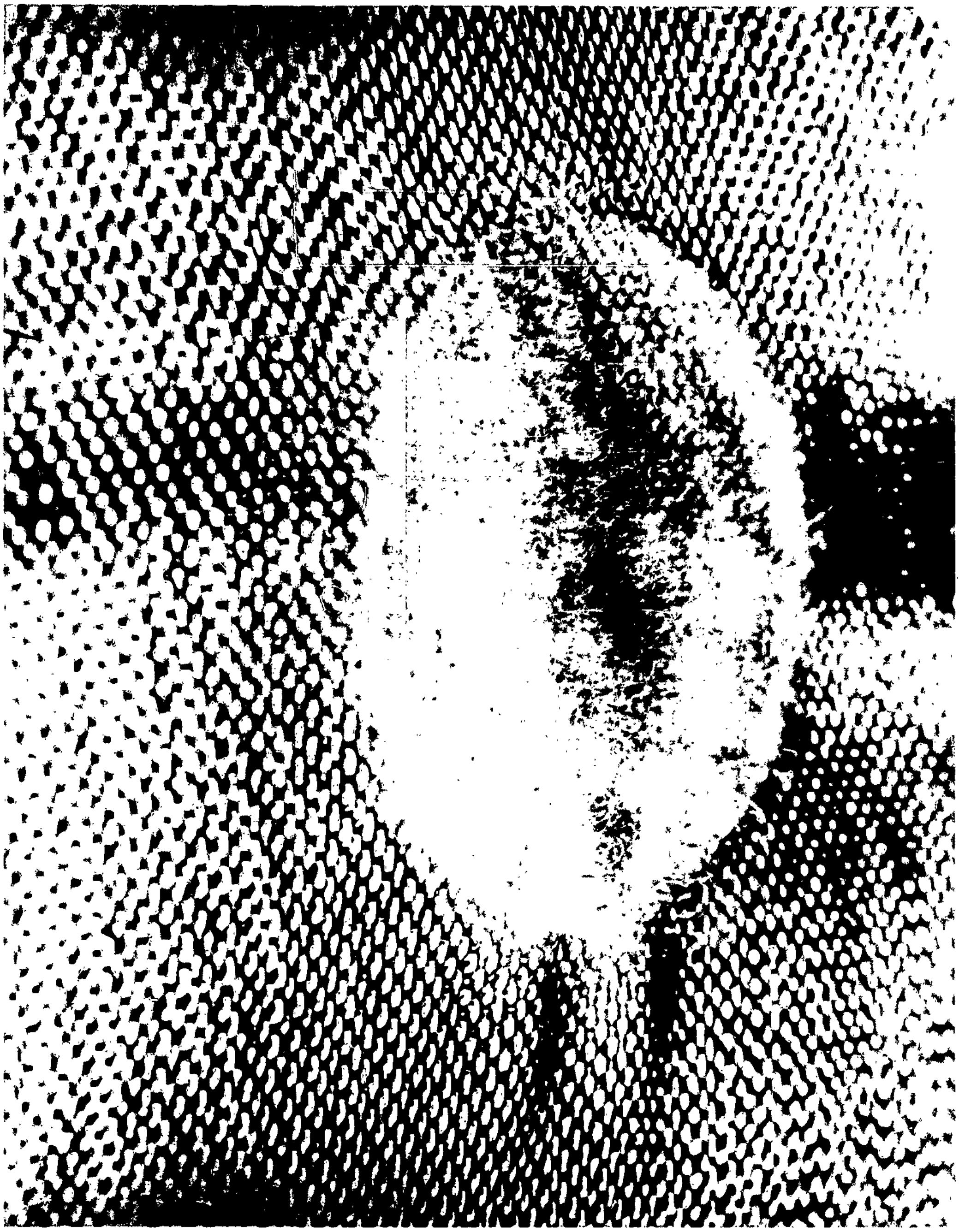


Figure 6. Damage from High Intensity Sound
(c) Woven Glass Cloth No. 8 after
30 Minutes at 160 db

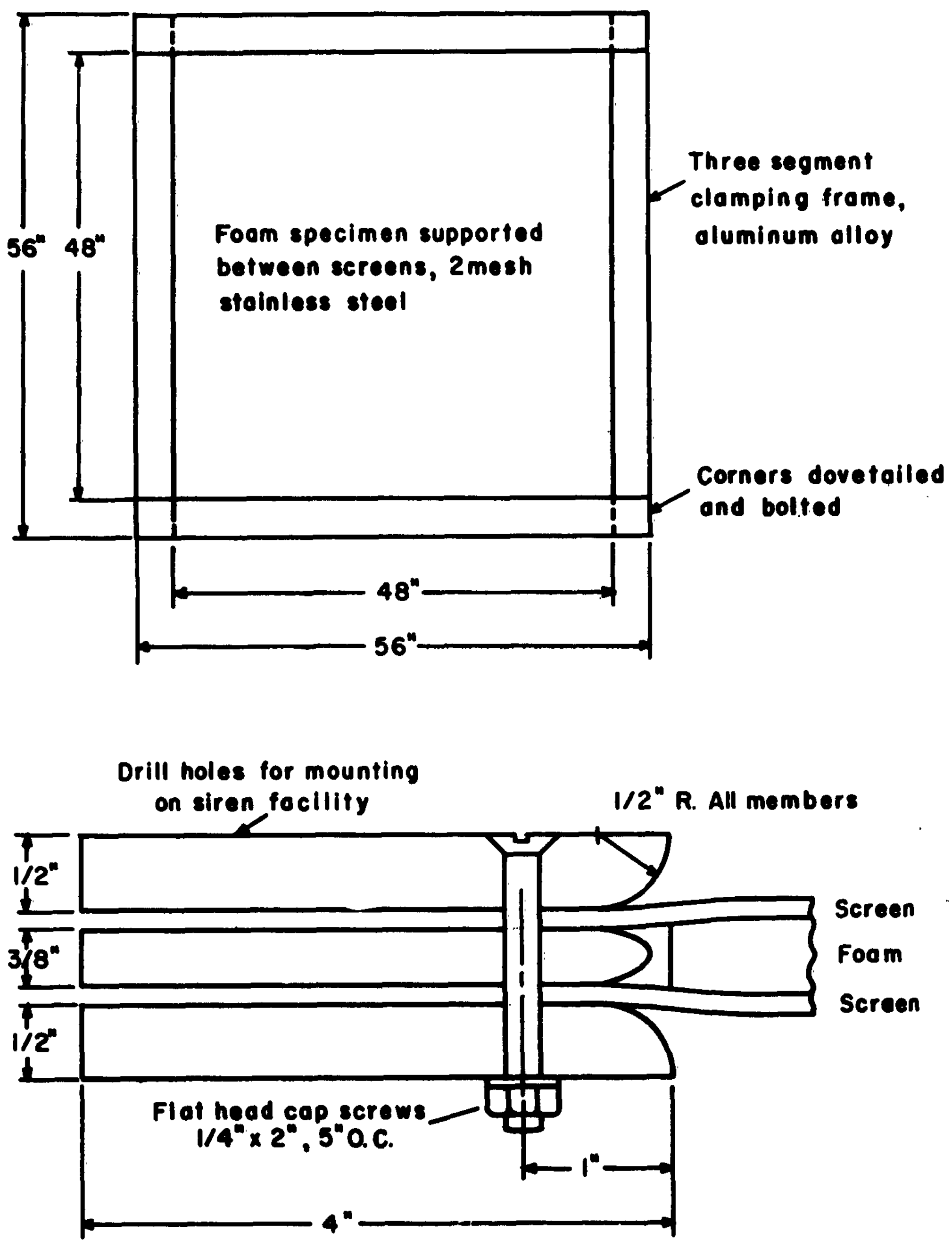


Figure 7. Clamping Frame for Extended Life Test

Figure 8. Photograph of Specimen Mounted in Siren Facility

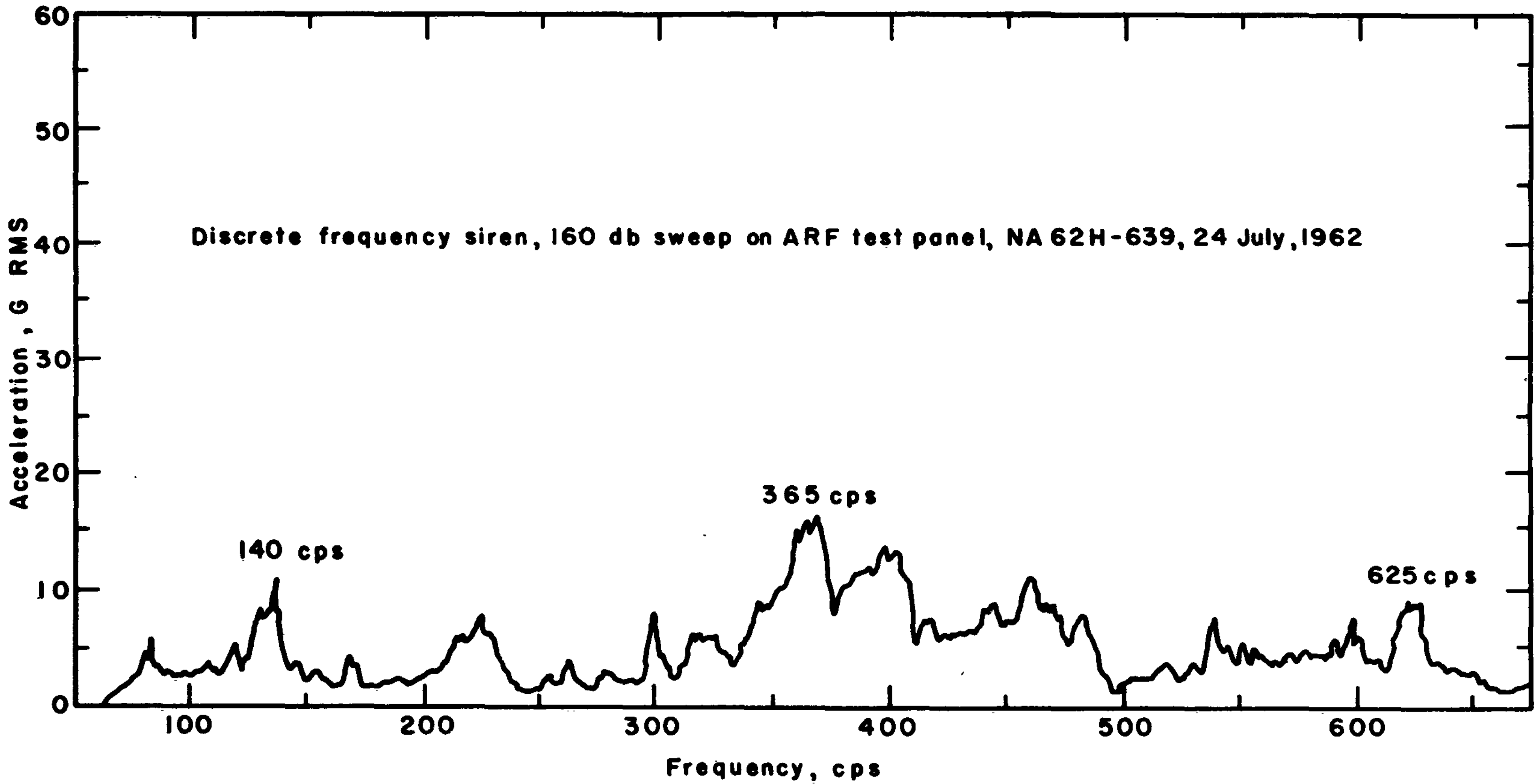


Figure 9. Acceleration Record for Accelerometer at Center of Extended Life Test Specimen

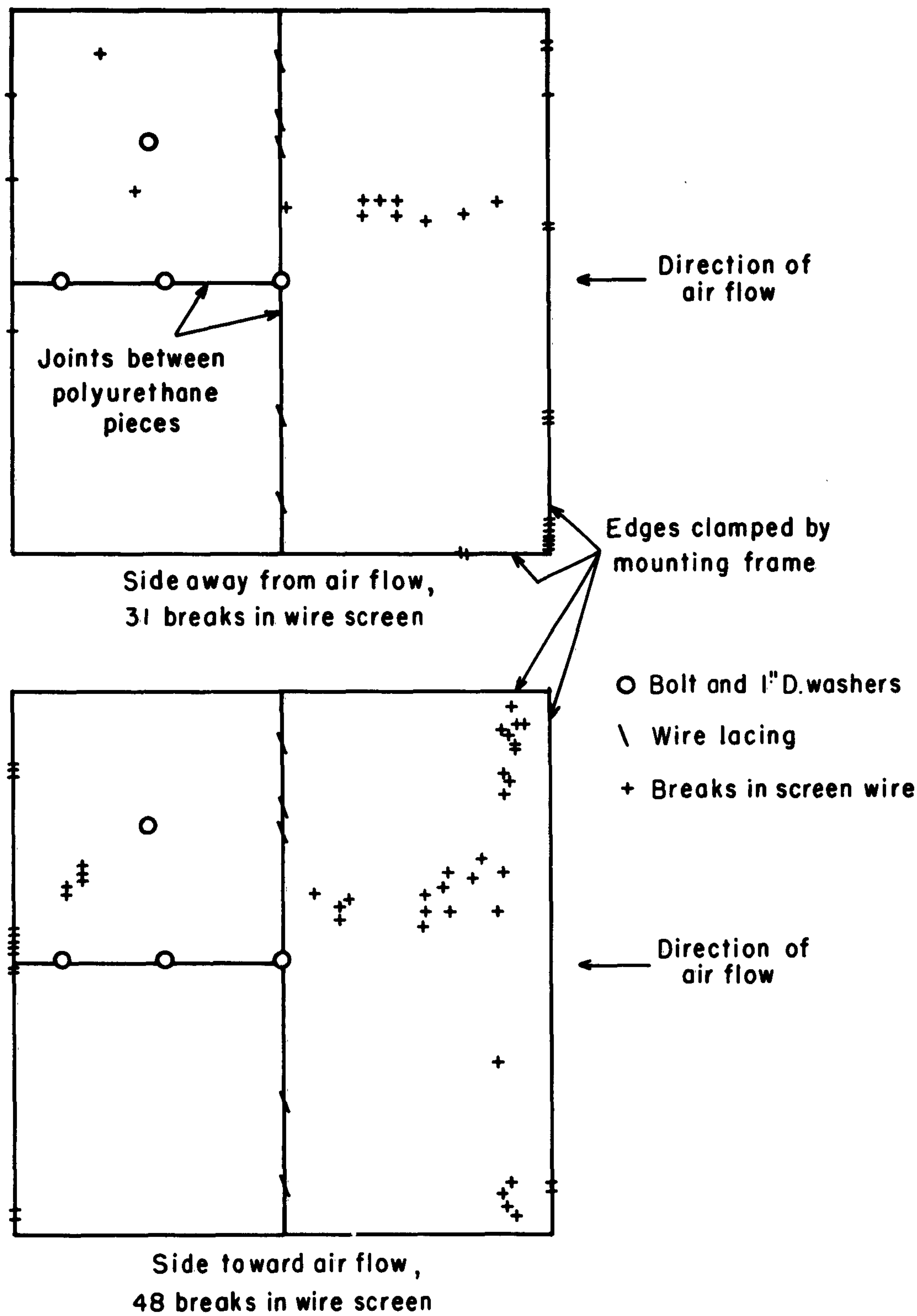


Figure 10. Location of Breaks in Wire Screens after 78 Hours at 157 db

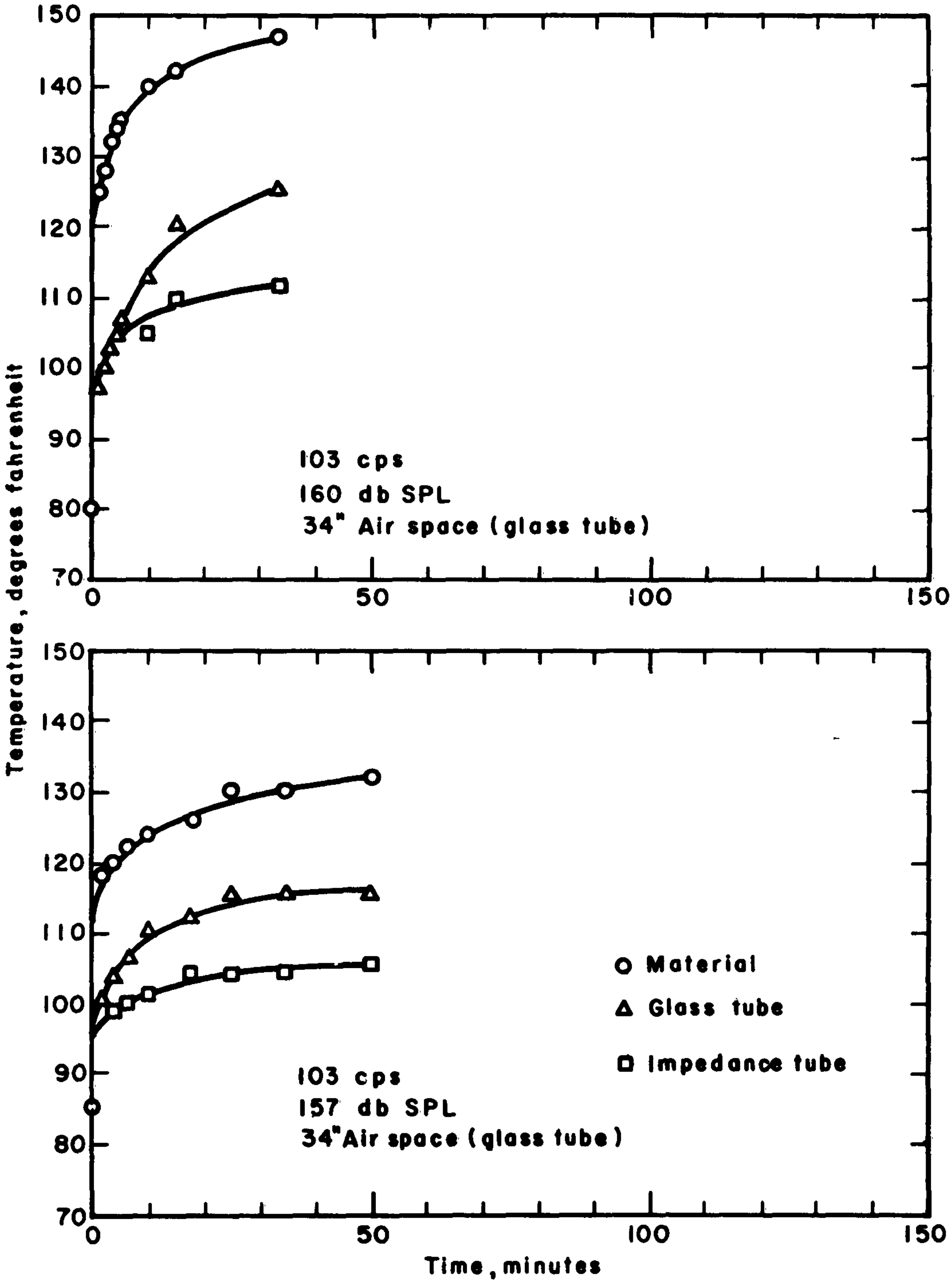


Figure 11. Temperature Rise at 103 cps for Polyurethane, 1/2" No. 3B, 1/4 Wavelength Backing

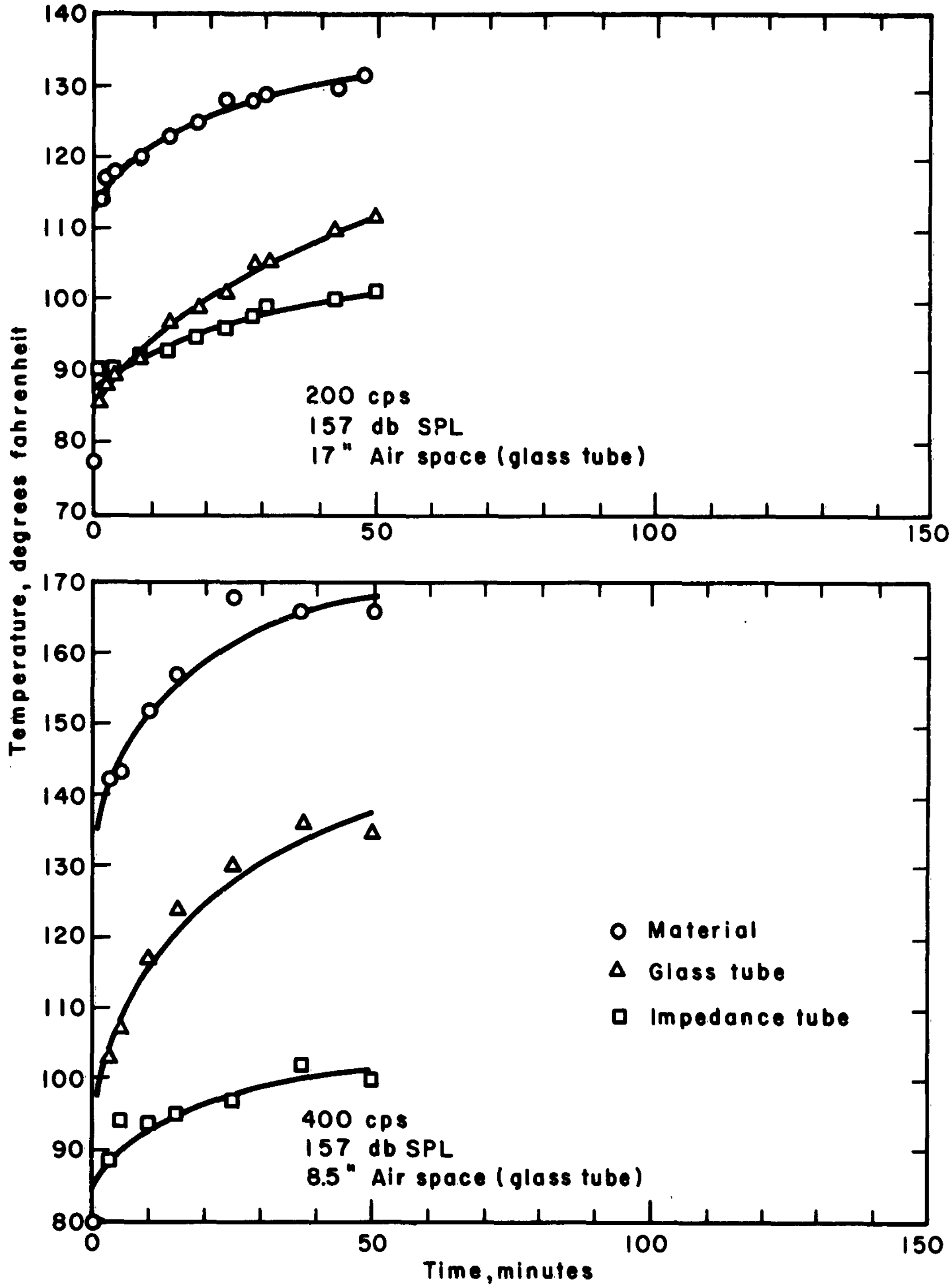


Figure 12. Temperature Rise at 200 and 400 cps for Polyurethane, 1/2" No. 3B, 1/4 Wavelength Backing

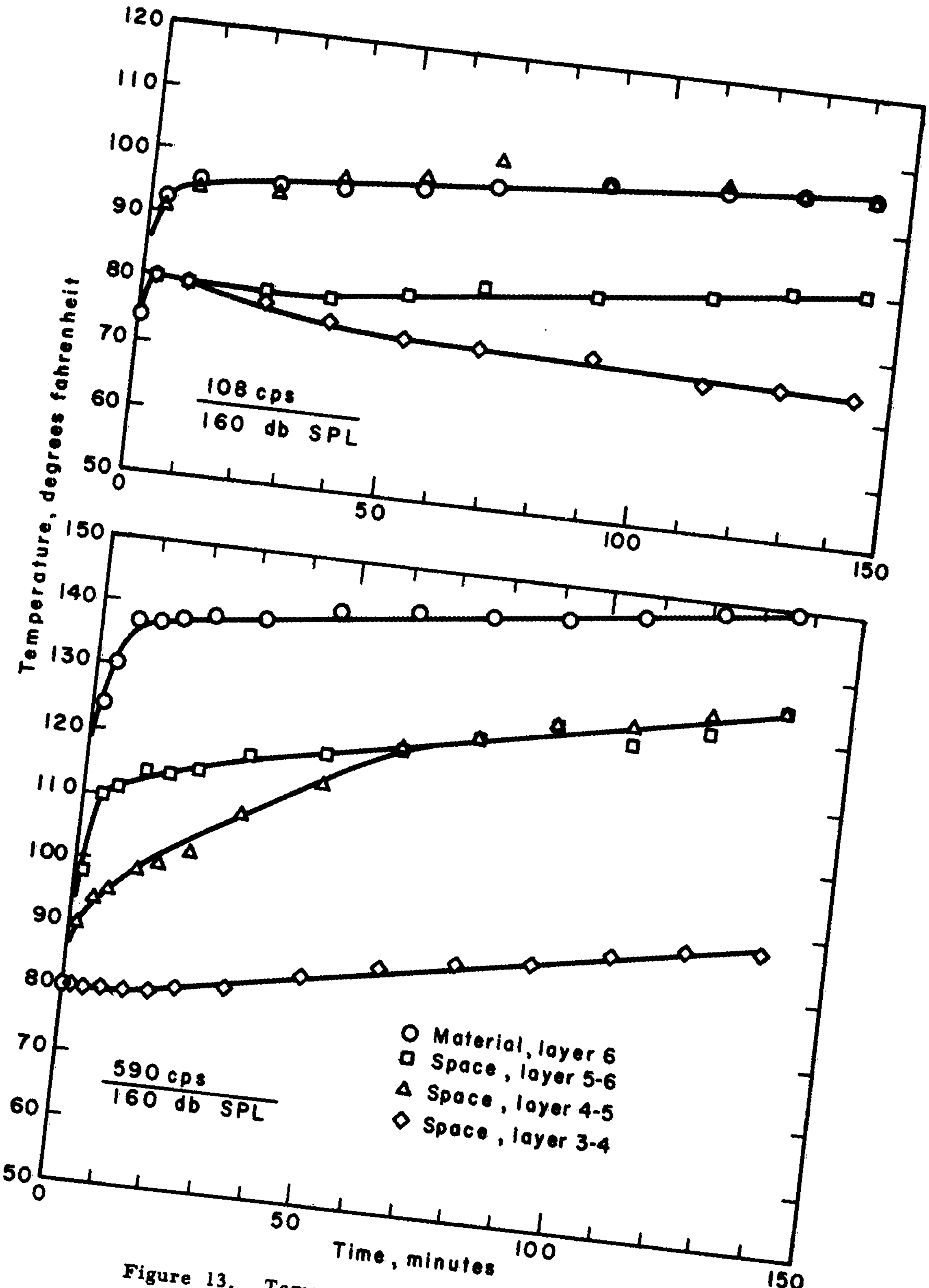


Figure 13. Temperature Rise for System No. 11

Figure 14. Scale Model Showing a Method of Supporting Collapsible Layer Treatment

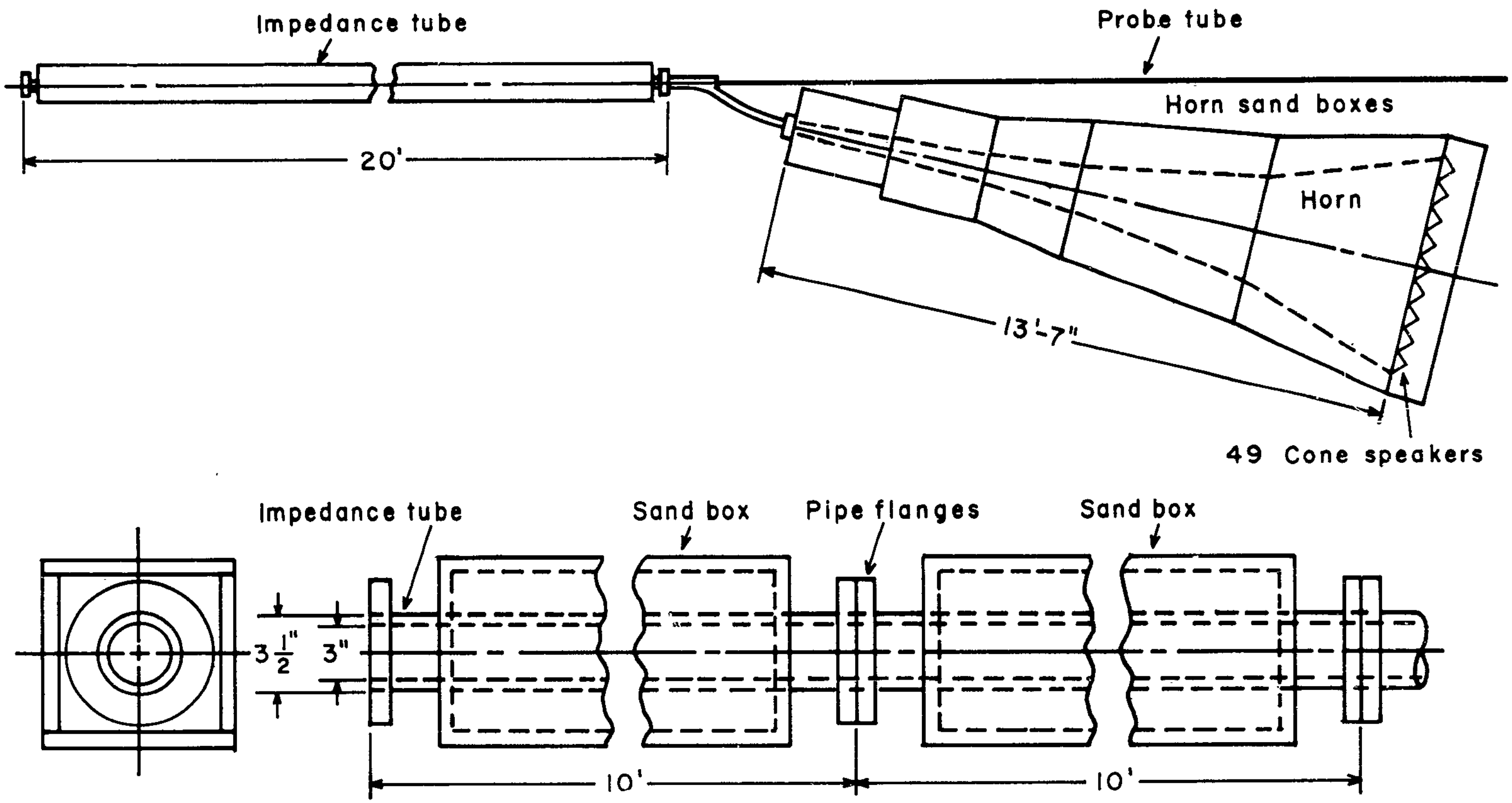


Figure 15. Low Frequency Impedance Tube

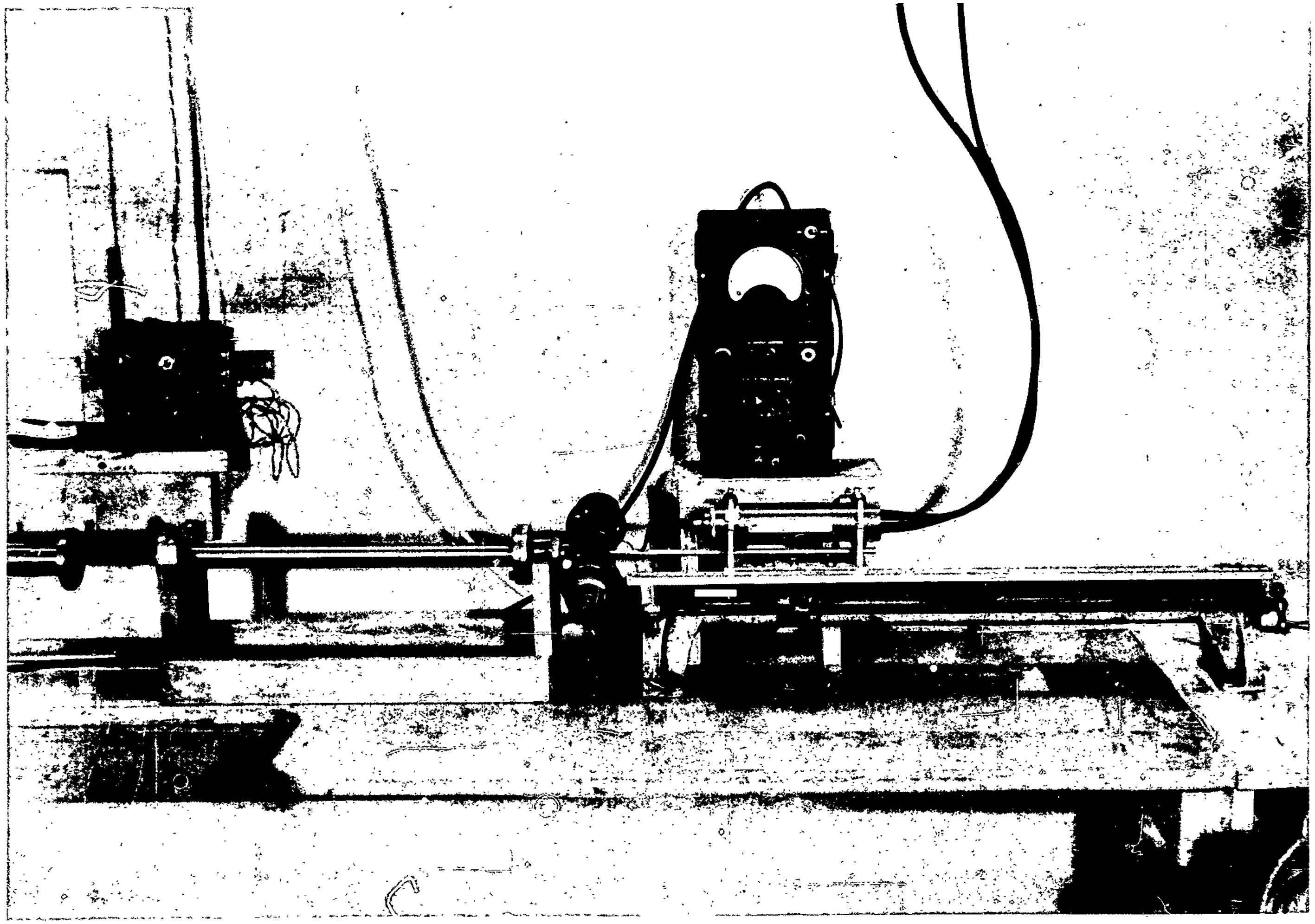


Figure 16. High Frequency Impedance Tube

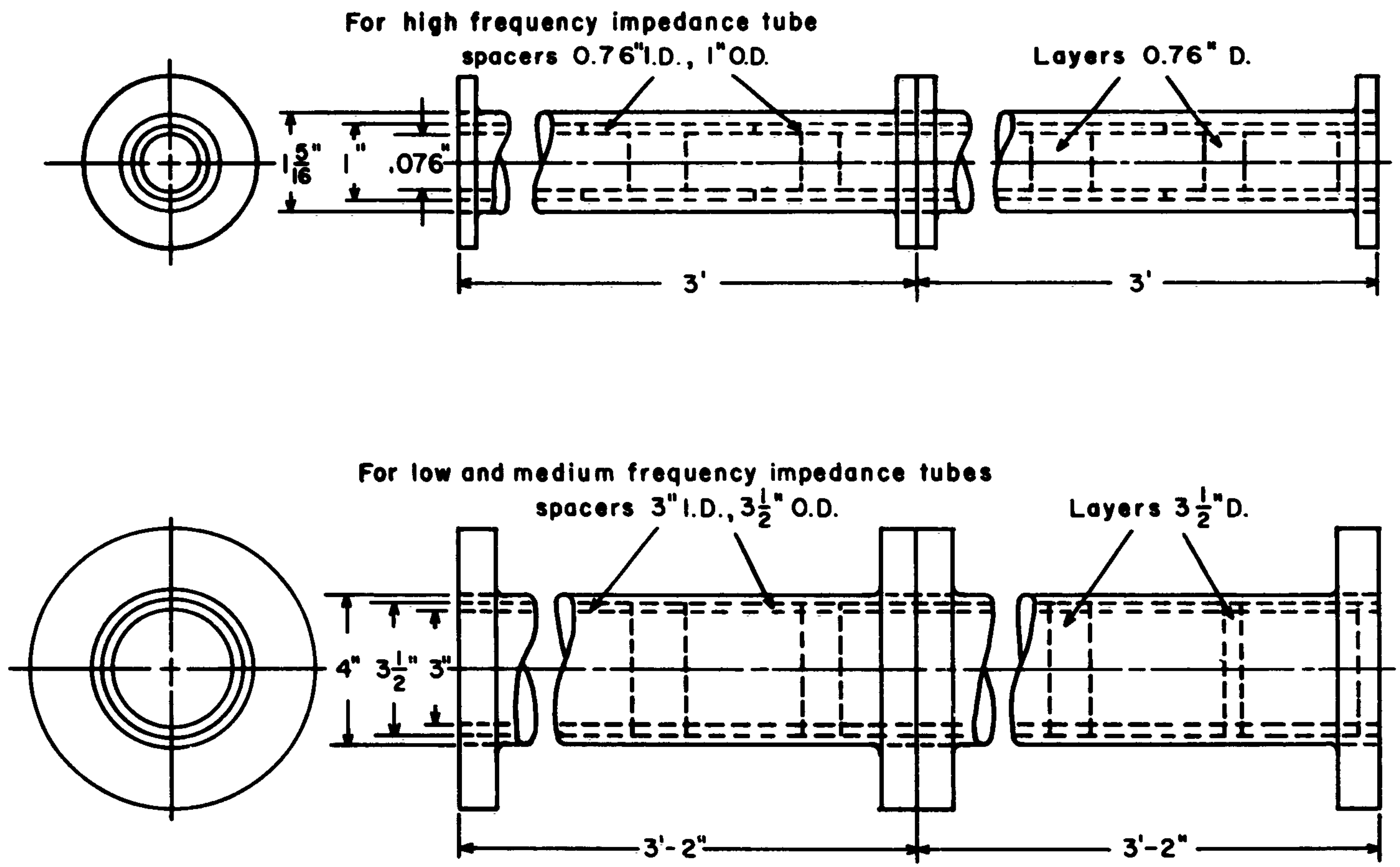


Figure 17. Layer System Sample Holders

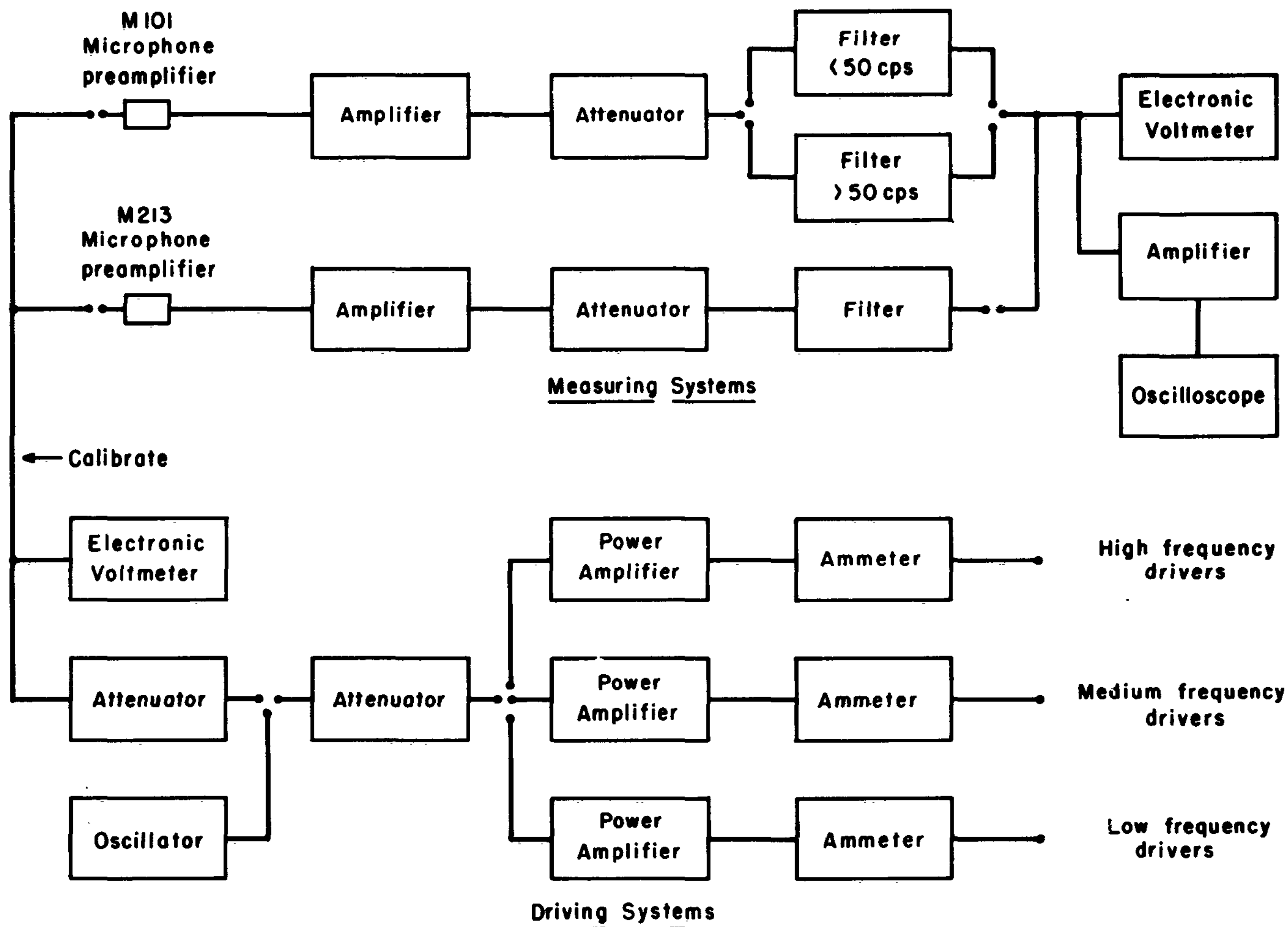


Figure 18. Block Diagram of Driving and Measuring Systems

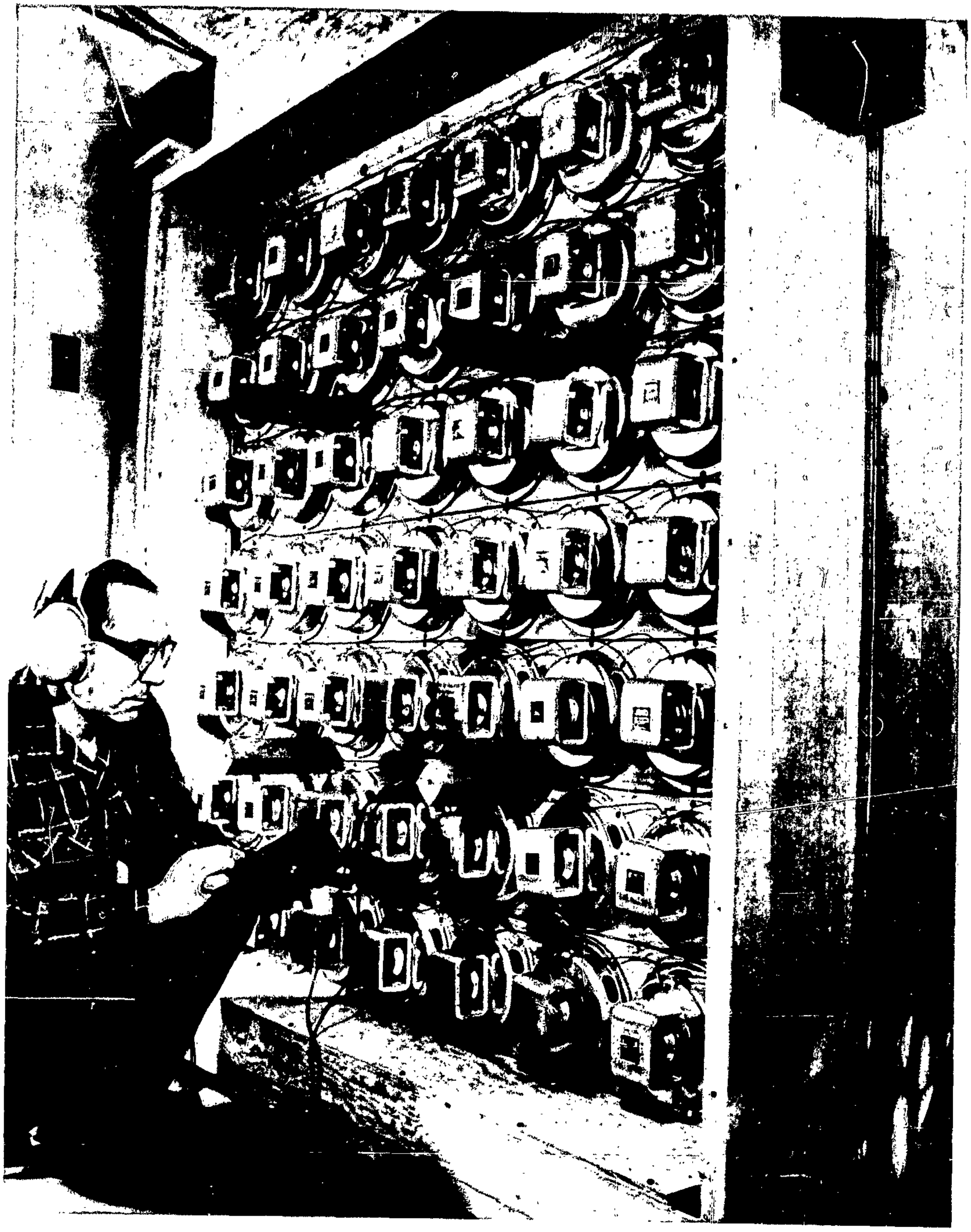


Figure 19. Drivers and Horn for Low Frequency Impedance Tube

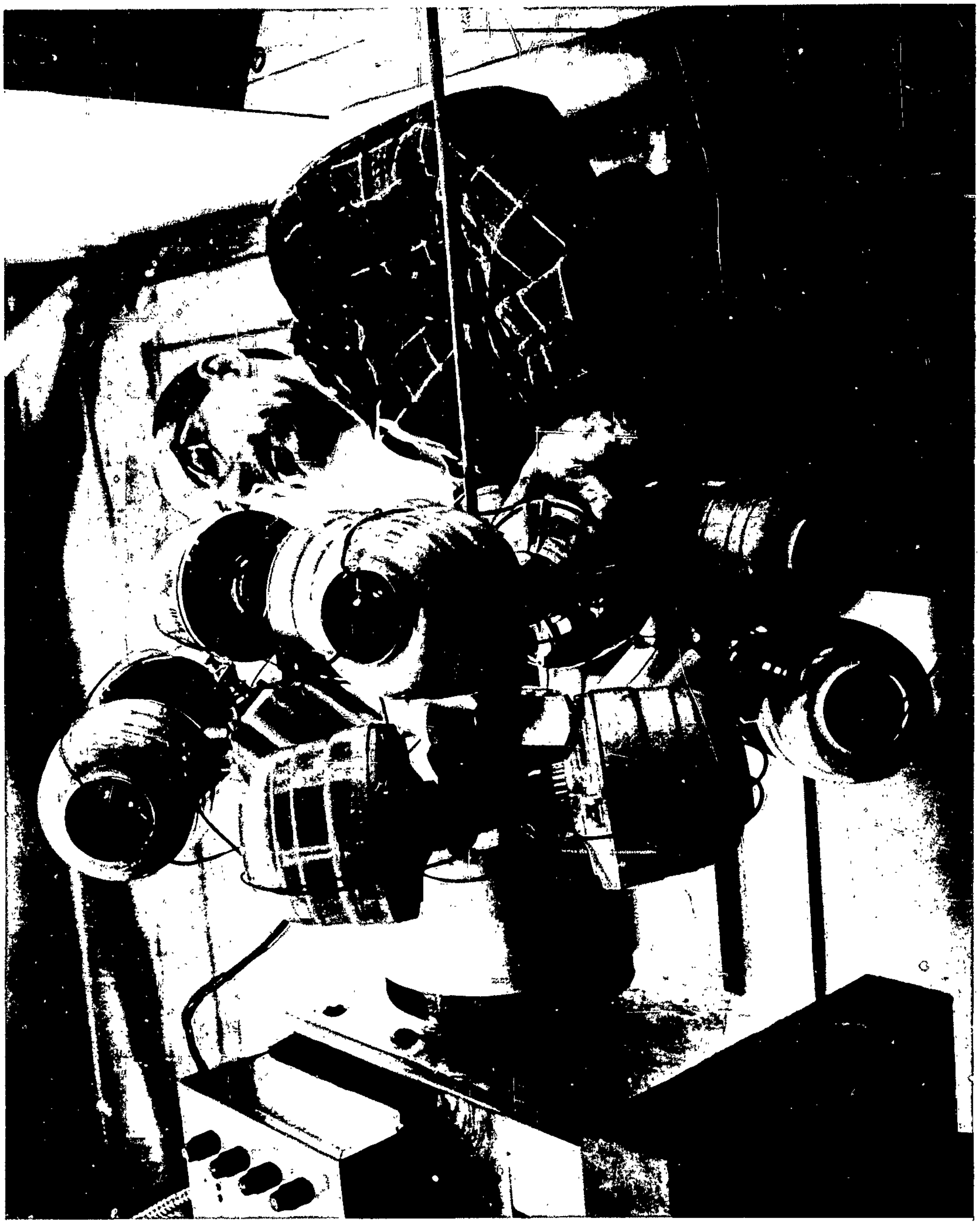


Figure 20. Drivers for Medium Frequency Impedance Tube

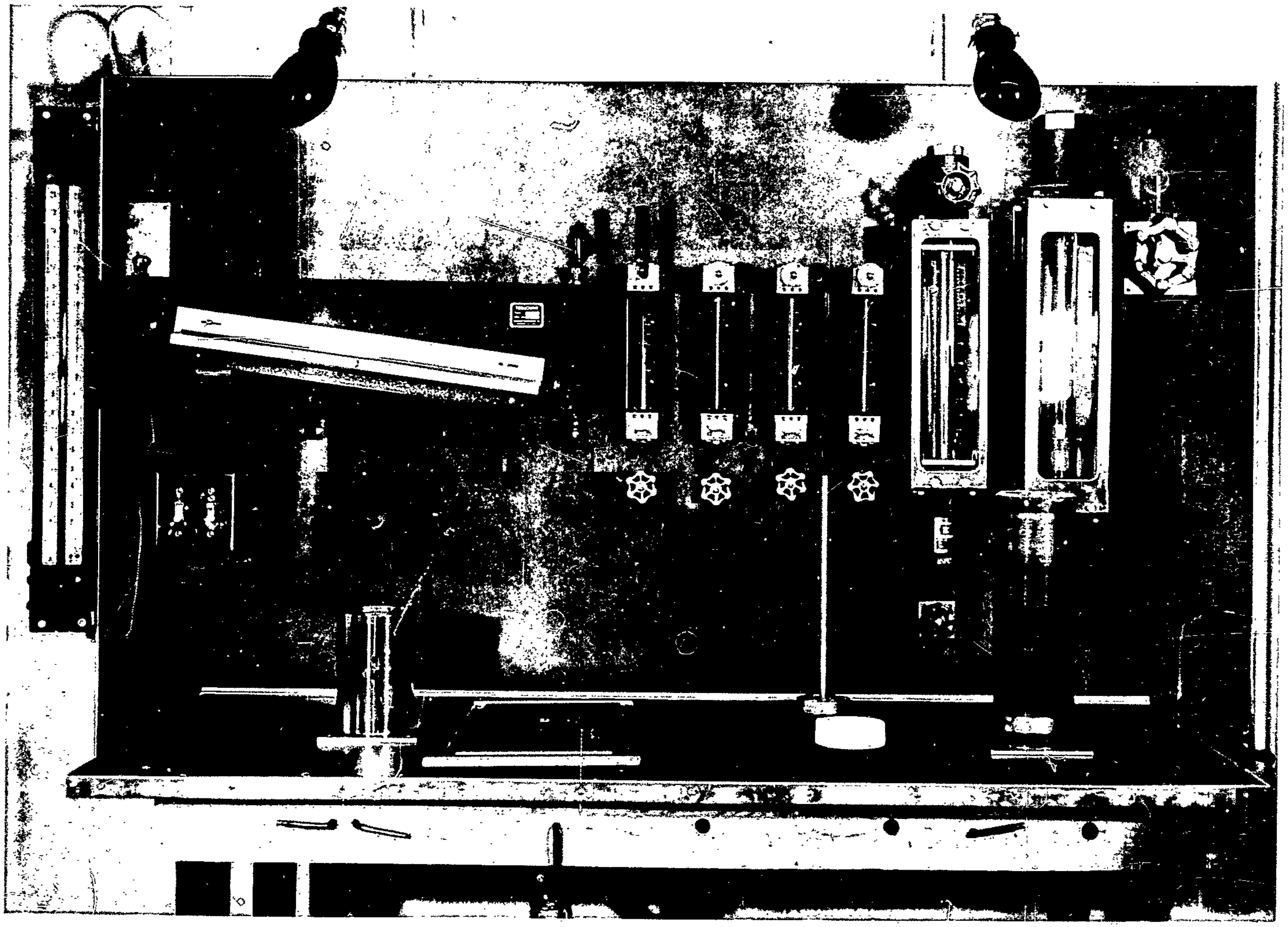


Figure 21. DC Flow Resistance Equipment

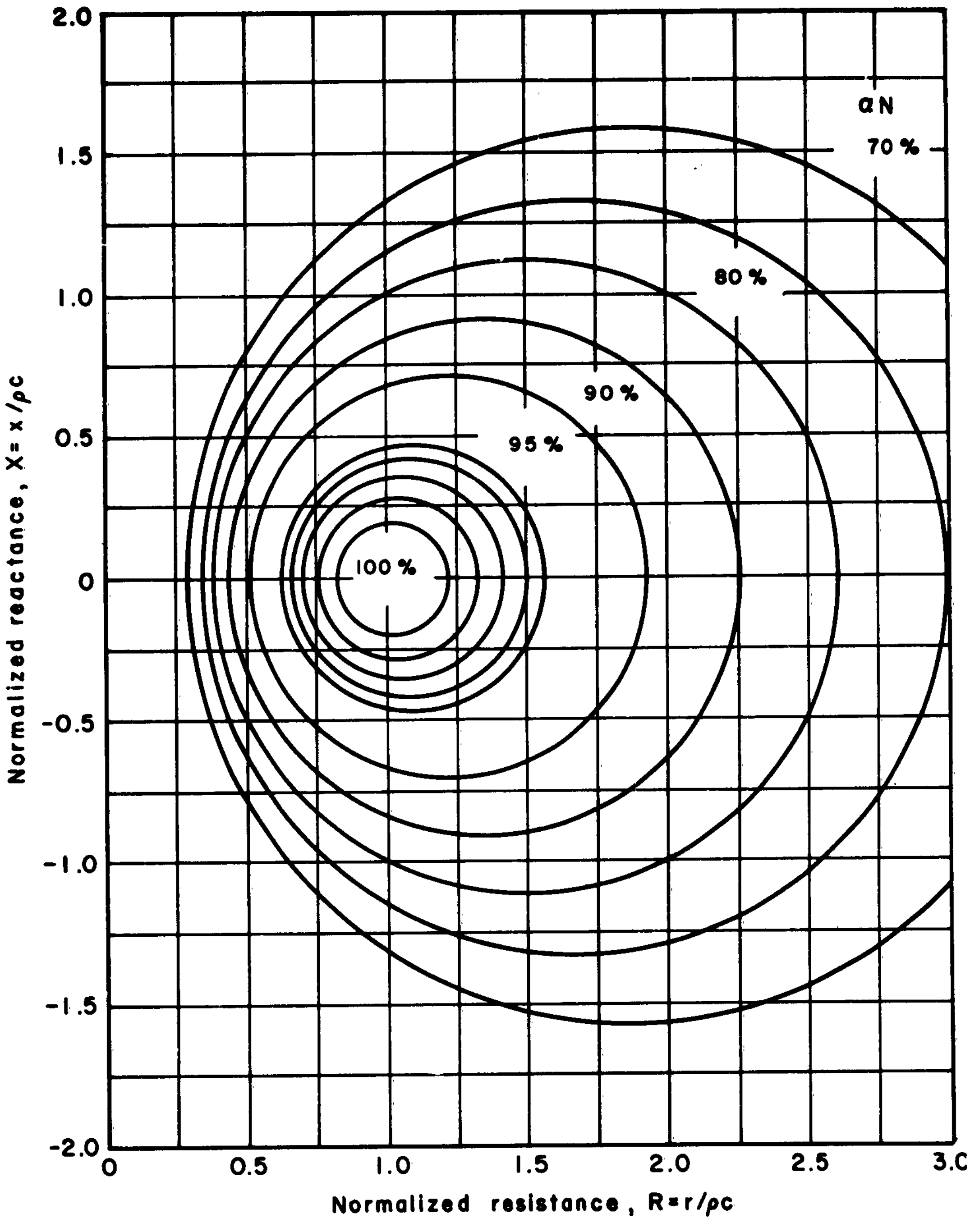
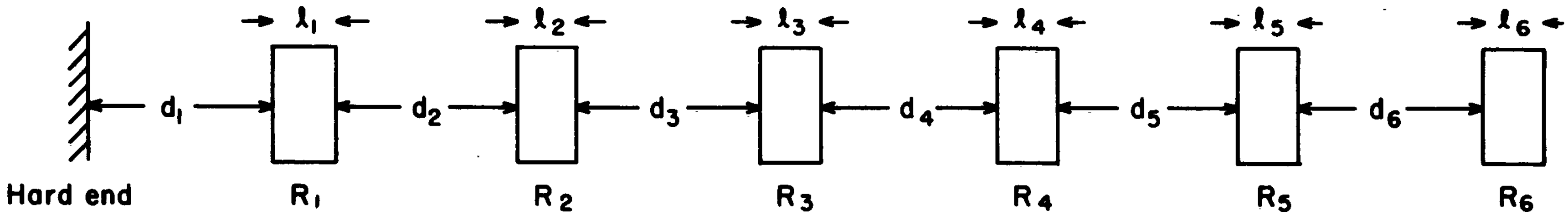
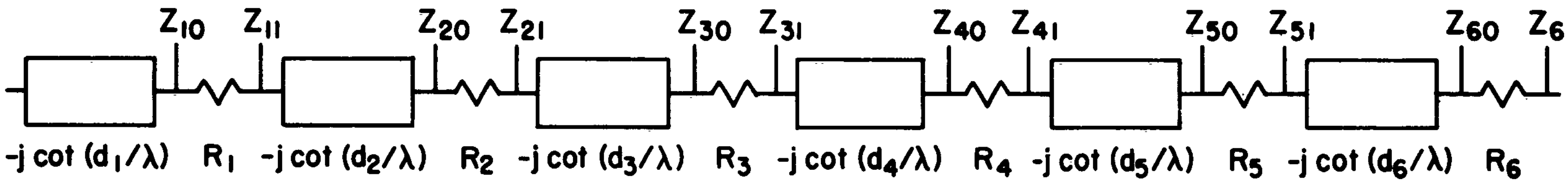


Figure 22. Normal Incidence Absorption Versus Impedance



Layer system



Equivalent transmission line for approximate calculation of α_N

$$Z_{10} = R_{10} + jX_{10} = \coth(-jd_1/\lambda) = -j\cot(d_1/\lambda)$$

$$Z_{11} = Z_{10} + R_1 = R_{10} + R_1 + jX_{10}$$

$$Z_{20} = \coth\left[-j\,d_2/\lambda + \coth^{-1}(Z_{11})\right], \text{etc.}$$

$$\alpha_N = 1 - \frac{|Z_{61} - 1|^2}{|Z_{61} + 1|^2} = \frac{4R_{61}}{(R_{61} + 1)^2 + X_{61}^2}$$

Figure 23. System Diagram for Calculation of α_N

TABLE I

DESCRIPTION OF MATERIALS

(a) Polyurethane Foam

Material		Thickness inches	Weight lb/ft^2	Normalized flow resistance at 140 db R_{DC}	R_{AC}
Polyurethane foam etched, Scott Paper Co.					
Black 10-30 pores/inch	No. 1	1.0	0.136	<0.03	
Gray 45 pores/inch	No. 2	1.0	0.131	0.10	
Green 60 pores/inch	No. 3	1.0 0.5	0.147 0.074	0.14 0.07	
Green 60 pores/inch sandwiched between two 20 mesh wire screens	No. 3A	0.5	0.57	0.07	0.13
Green 60 pores/inch weighted by two discs of 4 mesh hardware cloth	No. 3B	1.0 0.5	0.64 0.57	0.14 0.07	0.26 0.13
Beige 80 pores/inch	No. 4	1.0 0.5	0.144 0.072	0.32 0.16	
Beige 80 pores/inch weighted by two discs of 4 mesh hardware cloth	No. 4B	1.5 1.0 0.5	0.71 0.64	0.48 0.32	0.66 0.44
Polyurethane foam, Du Pont de Nemours Co.					
164G 19C/WC-207	No. 5	0.5		2.5	
160G 703/WS-603	No. 6	1.0 0.5		0.22 0.10	

TABLE I

DESCRIPTION OF MATERIALS

(b) Glass Wool

Material		Thickness inches	Weight lb/ft^2	Normalized flow resistance at 140 db R_{DC}	R_{AC}
Fiberglas, Owens Corning Fiberglas					
PF 105	No. 1	0.5	0.024	2.54	
PF 334	No. 2	0.5	0.020	0.26	
PF 334	No. 3	1.0	0.020	0.37	
used in systems 1 and 2		0.5	0.010	0.18	
PF 335	No. 4	0.5	0.031	0.32	
PF 336	No. 5	0.5	0.041	0.35	
PF 338	No. 6	0.5	0.062	0.57	
PF 339	No. 7	0.5	0.083	0.57	
AF 340	No. 8	0.5	0.063	0.54	
AF 360	No. 9	0.5	0.125	0.93	
Acoustifelt, Forty Eight Insulations Inc.					
2 lb density, 3 percent binder	No. 10	1.0	0.083	0.32	

TABLE I

DESCRIPTION OF MATERIALS

(c) Metallic Materials

Material				Thickness	Weight	Normalized flow resistance at 140 db	
				inches	lb/ft^2	R_{DC}	R_{AC}
Stainless wire screen, Ludlow-Saylor Wire Cloth Co.							
Mesh size /inch	Wire diam. inch	Open area %					
20	0.016	46.2	Type 304 No. 1		0.473	0.0082	
50	0.009	30.3	Type 304 No. 2		0.244	0.020	
60	0.009	21.3	Type 304 No. 3		0.285	0.022	
60	0.011	11.7	Type 304 No. 4		0.429	0.031	
100	0.0045	30.3	No. 5		0.121	0.022	
100	0.0045 Sandwiched between 2 20 mesh screens, No. 1	30.3	No. 5A		1.07	0.035	0.09
200	0.0021	33.6	No. 6		0.055		
200	0.0021 Sandwiched between 2 20 mesh screens, No. 1	33.6	No. 6A		1.00	0.046	
Fibermetal							
Special low resistance sample 1 layer			No. 7	0.046			

TABLE I

DESCRIPTION OF MATERIALS

(d) Woven Glass Cloth

Material		Thickness	Weight	Normalized flow resistance at 140 db	
		inches	lb/ft^2	R_{DC}	R_{AC}
J. P. Stevens Co.					
No. 354 cloth, 2 layers sandwiched between 2 20 mesh wire screens	No. 1A			0.033	0.09
strand material x 600 chopped, leno weave, 2 layers sandwiched between 2 20 mesh wire screens	No. 2A			0.019	
Hess Goldsmith Co.					
No. 857, 1 layer sandwiched between 2 20 mesh wire screens	No. 3A			0.49	
No. I-8087, 1 layer sandwiched between 2 20 mesh wire screens	No. 4A			0.049	0.12
Cadillac Plastic Co.					
6 oz.	No. 5			0.068	
7.5 oz.	No. 6			0.030	
8.5 oz.	No. 7			0.163	
10 oz.	No. 8			0.060	

TABLE II

EFFECT OF LAYER SURFACE DENSITY ON CALCULATED ABSORPTION OF SYSTEM 10

Surface Density per Layer lb/ft^2	α_N Calculated (percent) Frequency cps 20	30	50	75
∞	55	79	91	100
0.5	58	86	98	99
0.3	56	87	100	98
0.2	44	84	100	97
0.1	25	42	91	91
	α_n Measured in Impedance Tube			
	97.4*	87	96	100

*Measurement made at 22.5 cps

TABLE III

DESCRIPTION OF LAYER SYSTEMS

(a) Systems 1 - 4

Layer no.	Clear distance to previous layer inches	Thick-ness each layer inches	Weight each layer lbs/ft^2	Material (see Table I)	Normalized flow resistance each layer at 140 db. R_{DC}	R_{AC}
				System No. 1		
1	7	1.0	0.020	G. W.-No. 3 (1/2"+1/2")	0.37	
2	9	1.0	"	"	"	
3	11	1.0	"	"	"	
4	13	1.0	"	"	"	
5	15	1.0	"	"	"	
6	17	1.0	"	"	"	
				System No. 2		
1	17	1.0	0.020	G. W.-No. 3 (1/2"+1/2")	0.37	
2	15	1.0	"	"	"	
3	13	1.0	"	"	"	
4	11	1.0	"	"	"	
5	9	1.0	"	"	"	
6	7	1.0	"	"	"	
				System No. 3		
1	7	1.5	0.216	P. U.-No. 4 (1" + 1/2")	0.48	0.66
2	9	1.5	"		"	"
3	11	1.0	0.144	P. U.-No. 4 (1")	0.32	0.44
4	13	1.0	"		"	"
5	15	0.5	0.074	P. U.-No. 3 (1/2")	0.07	0.13
6	17	0.5	"	"	"	"
				System No. 4		
1	17	1.5	0.216	P. U.-No. 4(1" + 1/2")	0.48	0.66
2	15	1.5	"	"	"	"
3	13	1.0	0.144	P. U.-No. 4 (1")	0.32	0.44
4	11	1.0	"	"	"	"
5	9	0.5	0.074	P. U.-No. 3 (1/2")	0.07	0.13
6	7	0.5	"	"	"	"

TABLE III

DESCRIPTION OF LAYER SYSTEMS

(b) Systems 5 - 8

Layer no.	Clear distance to previous layer inches	Thickness each layer inches	Weight each layer lbs/ft^2	Material (see Table I)	Normalized flow resistance each layer at 140 db. R_{DC}	R_{AC}
				System No. 5		
1	12	1.5	0.216	P.U.-No. 4 (1" + 1/2")	0.48	0.66
2	12	1.5	"	"	"	"
3	12	1.0	0.144	P.U.-No. 4 (1")	0.32	0.44
4	12	1.0	"	"	"	"
5	12	0.5	0.074	P.U.-No. 3 (1/2")	0.07	0.13
6	12	0.5	"	"	"	"
				System No. 6		
1	14	1.5	0.216	P.U.-No. 4 (1" + 1/2")	0.48	0.66
2	10	1.5	"	"	"	"
3	14	1.0	0.144	P.U.-No. 4 (1")	0.32	0.44
4	10	1.0	"	"	"	"
5	14	0.5	0.074	P.U.-No. 3 (1/2")	0.07	0.13
6	10	0.5	"	"	"	"
				System No. 7		
1	7	0.5	0.072	P.U.-No. 4 (1/2")	0.16	0.22
2	9	0.5	"	"	"	"
3	11	0.5	"	"	"	"
4	13	0.5	"	"	"	"
5	15	0.5	"	"	"	"
6	17	0.5	"	"	"	"
				System No. 8		
1	7	1.0	0.082	G.W.-No. 5 (1/2" + 1/2")	0.7	
2	9	1.0	"	"	"	
3	11	1.0	"	"	"	
4	13	1.0	"	"	"	
5	15	1.0	"	"	"	
6	17	1.0	"	"	"	

TABLE III

DESCRIPTION OF LAYER SYSTEMS

(c) Systems 9 - 11

Layer no.	Clear distance to previous layer inches	Thick-ness each layer inches	Weight each layer lb/ft^2	Material (see Table I)	Normalized flow resistance each layer at 140 db. R_{DC}	R_{AC}
				System No. 9		
1	17	1.5	0.216	P.U.-No. 4 (1" + 1/2")	0.48	0.66
2	11	1.5	"	"	"	"
3	15	1.0	0.144	P.U.-No. 4 (1")	0.32	0.44
4	9	1.0	"	"	"	"
5	13	0.5	0.074	P.U.-No. 3 (1/2")	0.07	0.13
6	7	0.5	"	"	"	"
				System No. 10		
1	11	1.5	0.216	P.U.-No. 4 (1" + 1/2")	0.48	0.66
2	13	1.5	"	"	"	"
3	9	1.0	0.144	P.U.-No. 4 (1")	0.32	0.44
4	15	1.0	"	"	"	"
5	7	0.5	0.074	P.U.-No. 3 (1/2")	0.07	0.13
6	17	0.5	"	"	"	"
				System No. 11 *		
1	11	1.5	0.71	P.U.-No. 4B (1" + 1/2")	0.48	0.66
2	13	1.5	"	"	"	"
3	9	1.0	0.64	P.U.-No. 4B (1")	0.32	0.44
4	15	1.0	"	"	"	"
5	7	0.5	0.57	P.U.-No. 3B (1/2")	0.07	0.13
6	17	0.5	"	"	"	"

*System No. 11 differed from System No. 10 in having each layer weighted by two 2.5" diameter discs of hardware cloth, 1/4" mesh, 0.029 wire diameter.

TABLE III

DESCRIPTION OF LAYER SYSTEMS

(d) Systems 14 - 17

Layer no.	Clear distance to previous layer inches	Thickness each layer inches	Weight each layer lb/ft^2	Material (see Table I)	Normalized flow resistance each layer at 140 db. R_{DC}	R_{AC}
				System No. 14		
1	30	1.5	0.71	P. U. -No. 4B (1" + 1/2")	0.48	0.66
2	11	1.5	"	"	"	"
3	15	1.0	0.64	P. U. -No. 4B (1")	0.32	0.44
4	9	1.0	"	"	"	"
5	13	0.5	0.57	P. U. -No. 3B(1/2")	0.07	0.13
6	7	0.5	"	"	"	"
				System No. 15		
1	30	1.5	0.71	P. U. -No. 4B (1" + 1/2")	0.48	0.66
2	7	1.5	"	"	"	"
3	13	1.0	0.64	P. U. -No. 4B (1")	0.32	0.44
4	9	1.0	"	"	"	"
5	11	0.5	0.57	P. U. -No. 3B (1/2")	0.07	0.13
6	15	0.5	"	"	"	"
				System No. 16		
1	30	1.5	0.71	P. U. -No. 4B (1" + 1/2")	0.48	0.66
2	11	1.0	0.64	P. U. -No. 4B (1")	0.32	0.44
3	9	1.0	"	"	"	"
4	15	0.5	0.57	P. U. -No. 3B (1/2")	0.07	0.13
5	7	0.5	"	"	"	"
				System No. 17		
1	30	1.5	0.71	P. U. -No. 4B (1" + 1/2")	0.48	0.66
2	9	1.0	0.64	P. U. -No. 4B (1")	0.32	0.44
3	11	1.0	"	"	"	"
4	7	0.5	0.57	P. U. -No. 3B (1/2")	0.07	0.13
5	15	0.5	"	"	"	"

TABLE III

DESCRIPTION OF LAYER SYSTEMS

(e) Systems 18 - 21

Layer no.	Clear distance to previous layer inches	Thick-ness each layer inches	Weight each layer lb/ft^2	Material (see Table I)	Normalized flow resistance each layer at 140 db. R_{DC}	R_{AC}
				System No. 18		
1	20	1.5	0.71	P.U.-No. 4B (1" + 1/2")	0.48	0.66
2	8	1.0	0.64	P.U.-No. 4B (1")	0.32	0.44
3	14	1.0	"	"	"	"
4	11	0.5	0.57	P.U.-No. 3B (1/2")	0.07	0.13
5	19	0.5	"	"	"	"
				System No. 19		
1	20	1.5	0.71	P.U.-No. 4B (1" + 1/2")	0.48	0.66
2	11	1.0	0.64	P.U.-No. 4B (1")	0.32	0.44
3	19	1.0	"	"	"	"
4	8	0.5	0.57	P.U.-No. 3B (1/2")	0.07	0.13
5	14	0.5	"	"	"	"
				System No. 20		
1	30	1.5	0.71	P.U.-No. 4B (1" + 1/2")	0.48	0.66
2	9	1.5	"	"	"	"
3	11	1.0	0.64	P.U.-No. 4B (1")	0.32	0.44
4	7	1.0	"	"	"	"
5	15	0.5	0.57	P.U.-No. 3B (1/2")	0.07	0.13
				System No. 21		
1	30	1.5	0.71	P.U.-No. 4B (1" + 1/2")	0.48	0.66
2	9	1.5	"	"	"	"
3	11	1.0	0.64	P.U.-No. 4B (1")	0.32	0.44
4	7	1.0	"	P.U.-No. 3B (1")	0.14	0.26
5	15	0.5	0.57	P.U.-No. 3B (1/2")	0.07	0.13

TABLE III

DESCRIPTION OF LAYER SYSTEMS

(f) Systems 22 - 25

Layer no.	Clear distance to previous layer inches	Thickness each layer inches	Weight each layer lb/ft^2	Material (see Table I)	Normalized flow resistance each layer at 140 db. R_{DC}	R_{AC}
				System No. 22		
1	20	1.5	0.71	P.U.-No. 4B (1" + 1/2")	0.48	0.66
2	11	1.0	0.64	P.U.-No. 4B (1")	0.32	0.44
3	8	1.0	"	"	"	"
4	19	1.0	0.64	P.U.-No. 3B (1")	0.14	0.26
5	14	0.5	0.57	P.U.-No. 3B (1/2")	0.07	0.13
				System No. 23		
1	20	1.5	0.71	P.U.-No. 4B (1" + 1/2")	0.48	0.66
2	11	1.5	"	"	"	"
3	8	1.0	0.64	P.U.-No. 4B (1")	0.32	0.44
4	19	1.0	0.64	P.U.-No. 3B (1")	0.14	0.26
5	14	0.5	0.57	P.U.-No. 3B (1/2")	0.07	0.13
				System No. 24		
1	11	1.5	0.71	P.U.-No. 4B (1" + 1/2")	0.48	0.66
2	13	1.5	"	"	"	"
3	9	1.0	0.64	P.U.-No. 4B (1")	0.32	0.44
4	6	1.0	"	"	"	"
5	10	1.0	0.64	P.U.-No. 3B (1")	0.14	0.26
6	8	0.5	0.57	P.U.-No. 3B (1/2")	0.07	0.13
7	15	0.5	"	"	"	"
				System No. 25 (System No. 11 collapsed, 30" to ceiling)		
1	30	1.5	0.71	P.U.-No. 4B (1" + 1/2")	0.48	0.66
2	1	1.5	"	"	"	"
3	1	1.0	0.64	P.U.-No. 4B (1")	0.32	0.44
4	1	1.0	"	"	"	"
5	1	0.5	0.57	P.U.-No. 3B (1/2")	0.07	0.13
6	1	0.5	"	"	"	"

TABLE IV

IMPEDANCE TUBE SPECIFICATIONS

Impedance tube	Low	Medium	High
Diameter, inches	3	3	0.76
Length, inches	240	36	15
Frequency range - cps	20 - 300	300 - 2000	1500 - 6000
Drivers	49 Cone speakers	16 Horn drivers	2 Horn drivers
Microphones	Massa M-101	Massa M-213	Massa M-213

TABLE V

LIST OF DRIVING EQUIPMENT

Oscillator

Hewlett Packard model 200 AB

Attenuators

Daven Attenuators

0 - 1 db in 0.1 db steps, type 2506

0 - 10 db in 1.0 db steps, type 2511

0 - 100 db in 10.0 db steps, type 2513

Power Amplifiers

Mc Intosh model M-60 audio amplifier

Callidyne model 68 vibration test amplifier

M. B. model T-51 vibration test amplifier

TABLE VI

LIST OF MEASURING EQUIPMENT

Low Frequency Impedance Tube Microphone Systems

Massa M-101 microphone
Massa M-103 preamplifier
Massa M-104 amplifier and power supply

Medium and High Frequency Impedance Tubes Microphone Systems

Massa M-213 microphone
Massa M-114 preamplifier
Massa M-185 amplifier and power supply

Western Electro-Acoustic Lab. Type 100 E amplifier

Attenuators

Daven attenuators

0 - 1	db in	0.1 db steps,	type 2506
0 - 10	db in	1.0 db steps,	type 2511
0 - 100	db in	10.0 db steps,	type 2513

Filters

Allison vairable low pass and high pass filters, model 2-BR
Scott sound analyzer, type 420 A

Voltmeter

Ballantine electronic voltmeter, model 300

Oscilloscope

Dumont, type 304 H

TABLE VII

LIST OF FLOW MEASURING INSTRUMENTS
(Brooks full view rotameters)

Type number	Range cm^3/sec
1100	0.1 - 3.6
1100	1.5 - 26.
1100	10. - 220.
1100	70 - 1,000.
10 - 1110 - VH	500 - 5,100.
13 - 1110 - VH	3,500 - 37,500.

TABLE VIII

CALCULATED ABSORPTION COEFFICIENTS FOR SIX LAYER SYSTEMS WITH EQUAL RESISTANCE PER LAYER AND SPACINGS OF SYSTEM NO. 1

R_{AC} per layer	.1	0.2	0.3	0.4	0.5
Frequency cps		α_N percent			
50.	71	93	99	99	97
94.4			94	95	95
100	65	87	94	95	96
141	78	95			
200	72			97	
472			80	80	81
500	53	74	83	87	89
519			94	96	96

TABLE IX

CALCULATED ABSORPTIONS, ASD ROOM

Surface, ft^2	Area, ft^2	$\alpha_N/100$	A, Sabins
	Untreated room		
Floor 50 x 70	3,500	0.02	70
Ceiling 50 x 70	3,500	0.02	70
Walls 2×40(70 + 50)	9,600	0.02	192
	16,600	0.02 Av.	332
	Extended treatment		
Floor 50 x 70	3,500	0.02	70
Ceiling 38 x 38	2,204	0.96	2,120
Walls 2×34(58 + 38)	6,528	0.96	6,270
	12,232	0.69 Av.	8,460
	Collapsed treatment		
Floor 50 x 70	3,500	0.02	70
Ceiling 38 x 38	2,204	0.90	1,984
Walls (concrete) 2×30 x (50 + 70)	7,200	0.02	144
Walls (vertical) 2×6.5 x (38 + 58)	1,248	0.90	1,123
Walls (horizontal) 2×6 x (38 + 70)	1,296	0.90	1,166
	15,448	0.29 Av.	4,487
	Collapsed treatment (ceiling panels removed)		
Floor 50 x 70	3,500	0.02	70
Ceiling 38 x 38	2,204	0.02	44
Walls (concrete) 2×30 x (50 + 70)	7,200	0.02	144
Walls (vertical) 2×10 x (38 + 58)	1,920	0.90	1,728
Walls (horizontal) 2×6 x (38 + 70)	1,296	0.90	1,166
	16,120	0.20 Av.	3,152

TABLE X

REVERBERATION TIMES, ASD ROOM

Treatment	A, Sabins	V, ft^3	T, sec
Untreated	332	140,000	20.7
Extended treatment	8,460	"	0.8 *
Collapsed treatment	4,487	"	1.5
Collapsed treatment with ceiling treatment removed	3,152	"	2.2

*This value is given for comparison purposes only, since reverberant field conditions do not hold in this case.

TABLE XI

DIFFERENCES BETWEEN TOTAL SOUND LEVEL AND DIRECT SOUND LEVEL FOR A NON-DIRECTIONAL SOURCE IN ASD ROOM

Room condition	$R = \frac{A}{1 - \alpha_a}$	Total level minus direct level	
		10 ft.	20 ft.
Extended treatment	27,300 ft^2	0 db	0 db
Collapsed treatment	6,340	3	6
Collapsed treatment with ceiling treatment removed	3,940	4	9
No treatment	339	14	19

Aeronautical Systems Division, Dir/Engineering Test, Sonic Branch, Wright-Patterson AFB, Ohio. Rpt Nr ASD-TDR-62-985. DEVELOPMENT OF A SUITABLE ANECHOIC TREATMENT FOR THE ASD SONIC FATIGUE FACILITY. Final report, Mar 63, 138pp. incl illus., tables, 10 refs.

Unclassified Report

Results are given for a research program leading to the design of an anechoic treatment for the test chamber of the ASD high intensity sound facility. The acoustical requirements for 96 percent absorption coefficient at normal incidences for a frequency range of 50-7000 cps and for sound pressure levels up to 160 db and the mechanical requirements for a collapsible treatment presented novel problems in design. The requirements were met by a treatment, six feet thick, composed of six layers of absorbing material irregularly spaced with the acoustical resistances per layer increasing from low values

(over)

1. Anechoic chambers
2. ASD Sonic Fatigue Facility

I. AFSC Project 4437
II. Contract AF 33(657)-7434
III. ARF Institute of Technology, Chicago, Ill.
IV. F. G. Tyzzer
V. Aval fr OTS
VI. In ASTIA collection

for layers at the incidence sound side to higher values for layers near the room surfaces. Tests in the high intensity impedance tube facility designed for the program showed that the normal incidence absorption coefficient of the treatment was 96 percent or higher over most of the frequency range from 50-7000 cps at sound pressure levels from 130 to 160 db. Fairly satisfactory results were also obtained for a five layer treatment subsequently designed. Etched polyurethane foam supported by wire screens was initially chosen as the layer material because of its resistance to damage in small scale life tests at particle velocities corresponding to a sound pressure level of 160 db. In subsequent accelerated life tests in the siren facility at North American Aviation, Columbus, Ohio there was no significant damage to a four by four foot specimen of material after 105 hours at sound pressure levels between 165 and 170 db except for failure of the supporting wire screens at about 78 hours.

Aeronautical Systems Division, Dir/Engineering Test, Sonic Branch, Wright-Patterson AFB, Ohio. Rpt Nr ASD-TDR-62-985. DEVELOPMENT OF A SUITABLE ANECHOIC TREATMENT FOR THE ASD SONIC FATIGUE FACILITY. Final report, Mar 63, 138pp. incl illus., tables, 10 refs.

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